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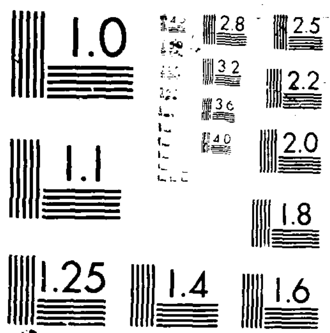
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RADC-TR-87-166, Vol I (of two)
Final Technical Report
October 1987

# TACTICAL RUBIDIUM FREQUENCY STANDARD (TRFS)

EG&G, Inc.

Thomas J. Lynch and William J. Riley

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19 ABSTRACT (Continue on reverse if necessary and identify by block number)

This report describes the accomplishments during a 3-year R&D program to design, develop, fabricate and evaluate two full scale engineering models of a Tactical Rubidium Frequency Standard (TRFS). The TRFS is a miniature atomic time and frequency source that is capable of operation in a harsh tactical military environment. In particular, it incorporates advances in miniaturization, ruggedness, fast warmup and high temperature operation that are required for aircraft applications. The report includes a detailed description of the TRFS design and the results of qualification tests on the two full scale engineering models. All program objectives were met.

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RB Physics Package
VCXO (Voltage Controlled Crystal Oscillator
Wideband Servo Loop
High Modulation Rate
Vibration Isolation



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# 1. INTRODUCTION

The EG&G Tactical Rubidium Frequency Standard (TRFS) is a high performance atomic frequency source capable of operation in a rugged tactical environment. This final Technical Report describes the EG&G TRFS design and its qualification.

The current EG&G TRFS program began in November, 1983 to design, develop, fabricate, test and evaluate two full scale engineering models of a Tactical Rubidium Frequency Standard.[1] This program followed previous work during 1982 involving basic TRFS development.[2] The TRFS requirements were given in a RADC specification dated 10 December 1982 based on Rev. B of Hazeltine Specification 332819 for their USAF SEEK-TALK program. After lengthy discussions starting in January 1984, the TRFS requirements were officially changed to a modified version of Rev. D of the Hazeltine specification in October, 1985. During this period the Hazeltine USAF program became HAVE-CLEAR and then EJS. A final contract modification in June, 1986 imposed Rev. E of the Hazeltine specification, including specific locations for the output and power connectors. These final specifications are included as Appendix A to this report.

The main technical challenge for the TRFS was to extend the operational capabilities of a rubidium frequency standard to demanding tactical aircraft environments. In particular, improvements were required in size, warmup time, upper temperature limit and performance under vibration.

All these objectives were met. The size requirement was met with a ultra-miniature Rb physics package and efficient electronics, without the use of hybrid microcircuits. Very fast warmup was obtained with

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1. Hanscom AFB Contract No. F19628-83-C-0175
2. Hanscom AFB Contract No. F19628-82-C-0055

relatively low demand power because of low mass and relatively cool ovens, and without compromising endurance. The upper operating temperature limit was extended by the use of active thermoelectric cooling without degrading stability. Performance objectives under vibration were met with a low g-sensitivity crystal oscillator tightly locked to a rugged Rb reference.

A photograph and outline drawing of the EG&G TRFS developed under this program are shown in Figure 1.1 and 1.2 respectively. Condensed specifications are shown in Table 1.1.

Overall, this program has fully met its goal to make available a tactical rubidium frequency standard for advanced tactical avionic systems.

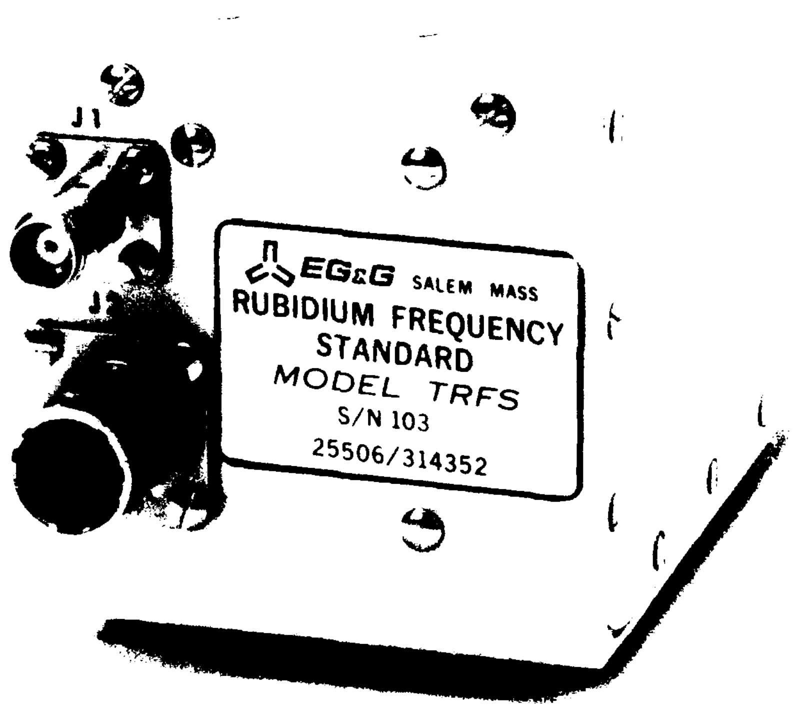
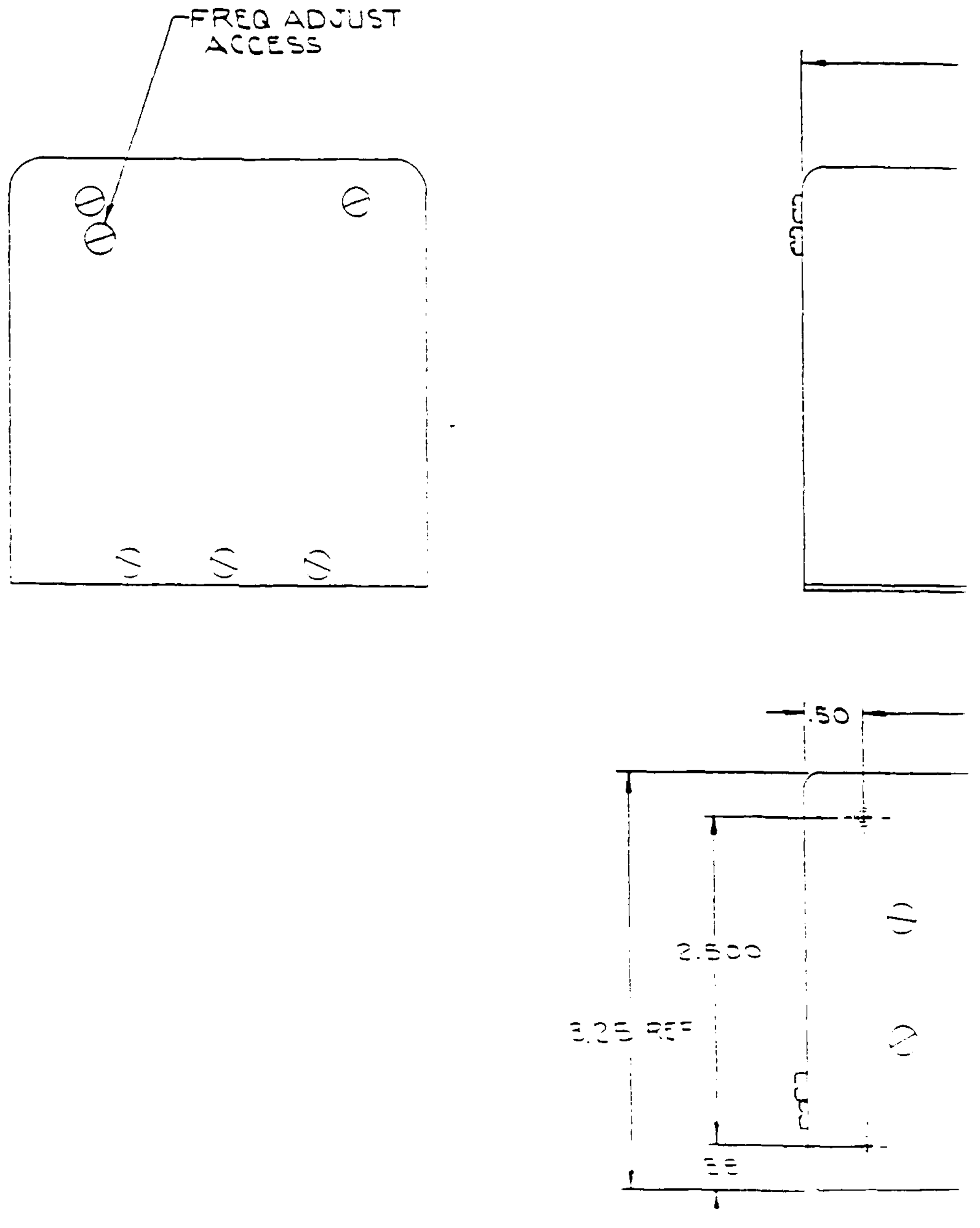



Figure 1-1. TRFS Photograph.

## TABLE 1.1

TRFS Condensed Specifications

| | | | | | |
|---|---|---|---|---|---|
| Output | 10 MHz sinewave<br>0.5V rms into 50Ω<br>Harmonics ≤ -30 dBc<br>Spurious ≤ -60 dBc<br>Accuracy $5\times10^{-11}$ at shipment | Voltage Sensitivity | $\leq 1\times10^{-11}$ for 10% input voltage change<br>$\leq 5\times10^{-11}$ over input voltage range<br>$\leq 1\times10^{-8}$ for 10 second heater voltage dropout | Salt Fog | MIL-STD-810, Method 509.1, Procedure I |
| Input Power | +28V dc heater per MIL-STD-704, Category B and MIL-STD-1275<br>+26 ± 4V dc electronic<br>50V, 1 sec transients<br>≤17W at +25°C<br>≤23W at -55°C<br>≤110W during warm-up | Magnetic Susceptibility | $\leq 2\times10^{-11}$/gauss | Fungus Resistance | All components and materials inherently fungus inert |
| Warm-Up | ≤4 min at -55 to $5\times10^{-10}$<br>≤1.5 min to lock<br>≤2 min to $1\times10^{-9}$ at +25°C<br>≤2.5 min to $5\times10^{-10}$ at +25°C | Retrace | $\leq 5\times10^{-11}$ | Bench Handling | MIL-STD-810, Method 516.2, Procedure V |
| Drift | $\leq 5\times10^{-10}$/year | Barometric Sensitivity | $\leq 1\times10^{-13}$/mbar | Acoustic Noise | MIL-STD-810, Method 515.2, Category A, Procedure I |
| Short-Term Stability | $\sigma_y(\tau) \leq 4\times10^{-11}\ \tau^{-1/2}$ for $1 \leq \tau \leq 100$ seconds | Environmental Conditions (General) | MIL-E-5400, Class 2 | Explosive Conditions | MIL-STD-810, Method 511.1, Procedure I |
| Phase Noise | ≤ -60 dBc/Hz at 1 Hz<br>≤ -80 dBc/Hz at 100 Hz<br>≤ -95 dBc/Hz at 1 kHz | Altitude | Sea Level to 70,000 feet | Sand and Dust | MIL-STD-810, Method 510.1, Procedure I |
| Trim Range | $\geq 3\times10^{-9}$ | Temperature/ Altitude | MIL-STD-810, Method 504.1, Procedure I, Category 6 | Rain | MIL-STD-810, Method 506.1, Procedure I |
| Settability | ≤[illegible] | Random Vibration | MIL-STD-810 Method 514.2 | EMI | MIL-STD-461-B Class A1 |
| Operating Temperature | -55°C to +71°C Ambient | Sinusoidal Vibration | MIL-STD-810, Method 514.2, Procedure VIII, Curve V | Reliability | MBTF ≥ 13,000 $A_{UF}$<br>MTBF ≥ 34,000 hours $G_F$<br>MTBF ≥ 21,000 hours $G_M$ |
| Storage Temperature | [illegible]°C to +95°C | Shock | MIL-STD-810, Method 516.2, Procedure I | Size | 3.25 x 3.25 x 4.5 inches |
| Temperature Sensitivity | $\leq 3\times10^{-10}$ over operating temperature range | Thermal Shock | MIL-STD-810, Method 503.1, Procedure I | Weight | ≤3.0 lbs |
| | | Acceleration | MIL-STD-810, Method 513.2, Procedure II | | |
| | | Humidity | MIL-STD-810, Method 507.1, Procedure II | | |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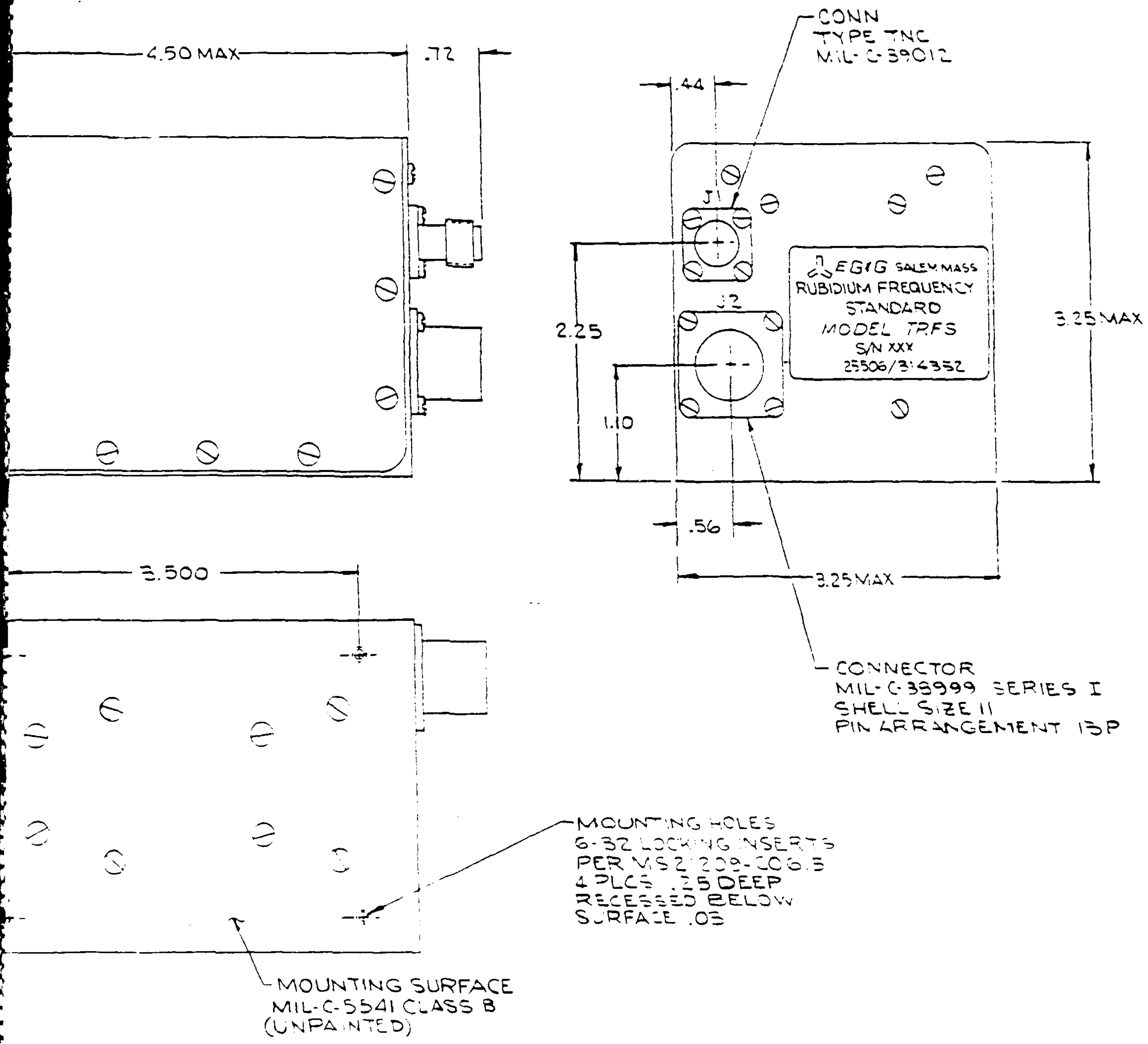


Figure 1.2. TRFS Outline.



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## 2. TECHNICAL COMPLIANCE

The EG&G TRFS design is fully compliant with the requirements of Rev. E of its specifications (see Appendix A), as verified by the results of the qualification tests described in Section 7 of this report. A summary of the qualification test compliance is shown in Table 7.0. With only minor exceptions correctable in subsequent hardware, all requirements are met. In several important respects, the requirements are exceeded. In particular the unit needs considerably less than the allowable warmup and steady-state power and is capable of full-performance operation at a higher than specified baseplate temperature.

## 3. DESIGN DESCRIPTION

The following report sections describe the general design of the EG&G TRFS. These descriptions are organized in accordance with the TRFS Functional Block Diagram of Figure 3.1.

The rubidium frequency standard is basically a crystal oscillator that is locked to a Rb atomic reference. The TRFS has particular design features that allow it to operate in a tactical military environment. Those features are discussed in more detail in Section 4 of this report.

3.1 Functional Block Diagram. A functional block diagram of the EG&G TRFS is shown in Figure 3.1. This configuration combines high performance, simplicity, and manufacturability. The major sections are:

1. A physics package section which acts as a frequency discriminator to produce an error signal which indicates the magnitude and sense of the difference in frequency between the applied rf excitation and the rubidium atomic resonance.

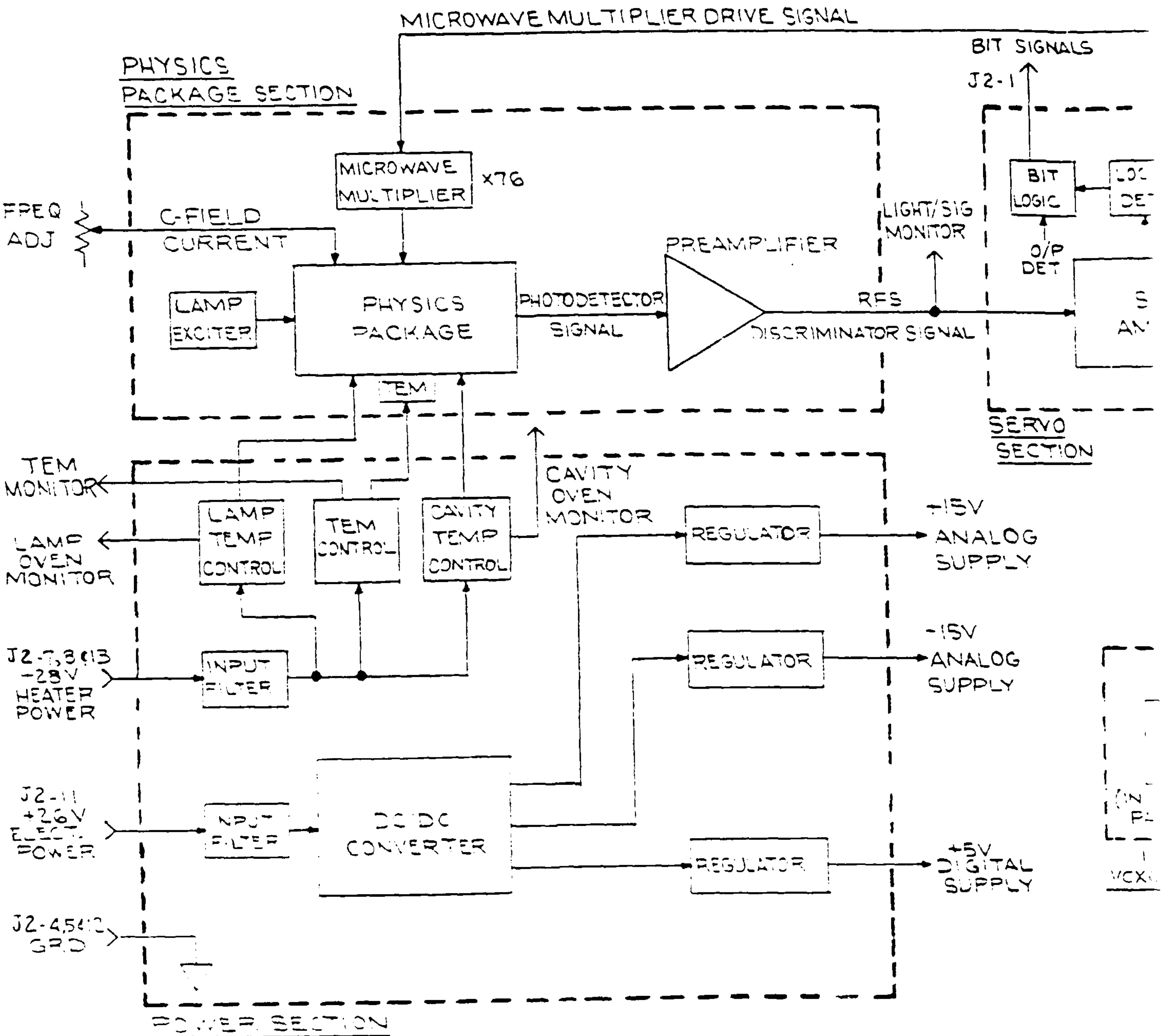
2. A VCXO section which contains a 10 MHz voltage controlled crystal oscillator (VCXO).

3. An RF section which contains a synthesizer to excite the rubidium resonance and circuits to produce the 10 MHz TRFS output.

4. A servo amplifier section which processes the Rb error signal to produce a control voltage for the 10 MHz VCXO.

5. A power section which provides "supply" voltages to the circuitry and has temperature controllers for the two physics package ovens, and a thermoelectric controller to extend the upper temperature range.

The electronic block diagram has a single frequency lock loop that contains a phase-locked loop synthesizer as a subloop. A particularly simple rf chain is used that has no critical tuned circuits. The servo amplifier is a low-complexity cascade detector configuration and the power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PREAMPLIFIER
BIT LOGIC
O/P DET
LAMP EXCITER
PHYSICS PACKAGE
PHOTODETECTOR SIGNAL
RFS
DISCRIMINATOR SIGNAL
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SERVO SECTION
TEM MONITOR
CAVITY OVEN MONITOR
LAMP TEMP CONTROL
TEM CONTROL
CAVITY TEMP CONTROL
LAMP OVEN MONITOR
REGULATOR
+15V ANALOG SUPPLY
J2-7,8 & 13
+28V HEATER POWER
INPUT FILTER
REGULATOR
-15V ANALOG SUPPLY
J2-11
+26V ELECT. POWER
INPUT FILTER
DC/DC CONVERTER
REGULATOR
+5V DIGITAL SUPPLY
J2-4,5 & 12
GRD
POWER SECTION

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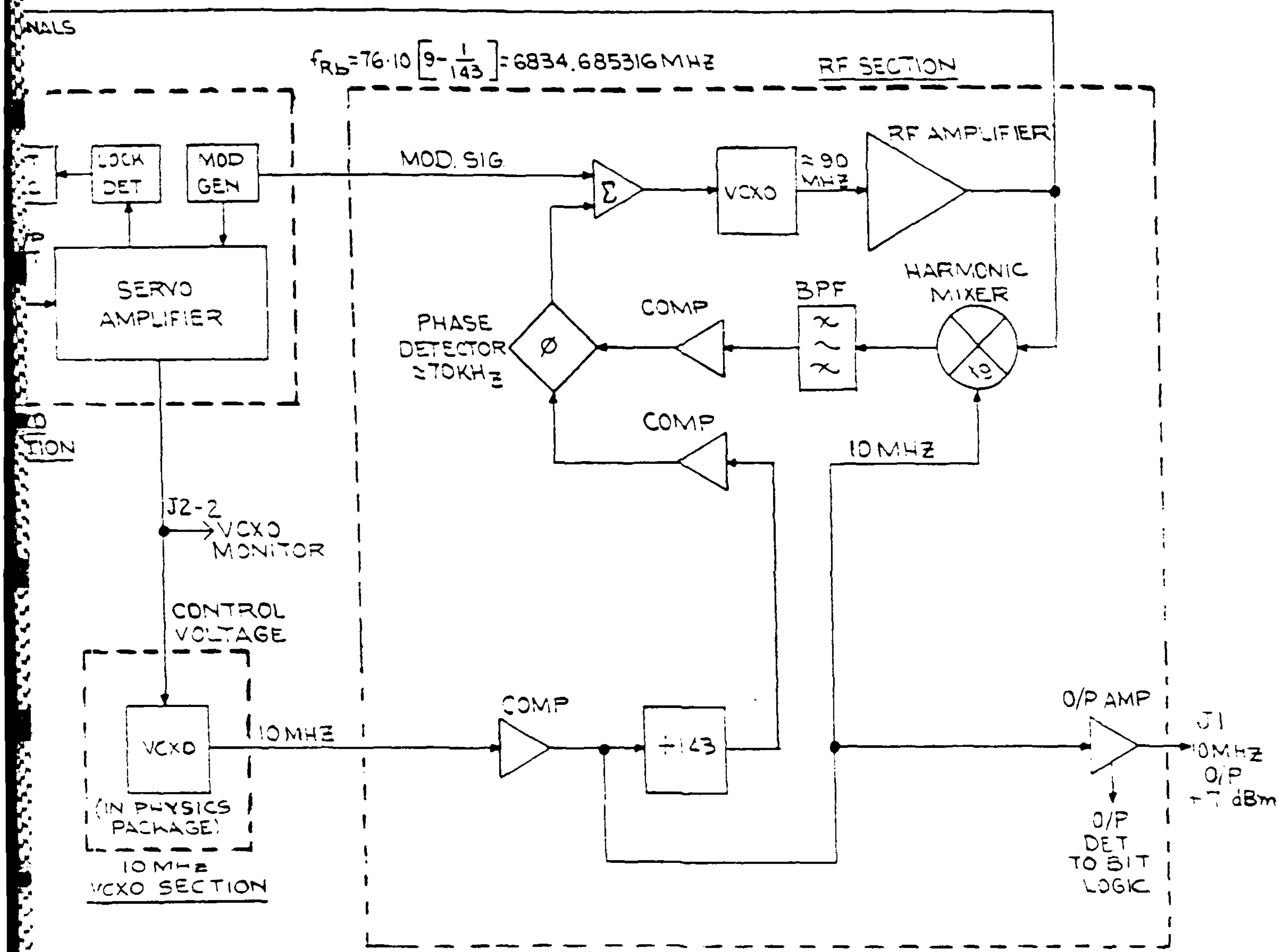



Figure 3.1. TRES Functional Block Diagram.

supply and temperature controller sections use efficient high frequency switching techniques. Monitors are provided for built-in test (BIT) and the 10-MHz VCXO control voltage.

3.2 Physical Layout. Physically, the TRFS consists of a physics package assembly and three main rf, servo and power electronic boards inside a 3¼" square by 4½" enclosure as shown in Figure 3.2.

The physics package assembly is at the center and is comprised of the following major elements (see Figures 3.3.1.1 and 3.3.1.2):

1. lamp exciter
2. lamp oven
3. microwave cavity
4. photodetector
5. 10 MHz crystal oscillator
6. double magnetic shields

The lamp oven contains the rubidium lamp. The microwave cavity contains the filter and absorption cells and a microwave multiplier.

The cylindrical magnetic shield of the physics package is supported within another (square) magnetic shield by resilient mounts. The elastic center of the mounts and the center of mass of the physics package are aligned so as not to excite rocking vibrational modes. These mounts are important to the thermal performance of the TRFS as well as to its behavior under shock and vibration. They are made of silicone rubber chosen for low temperature flexibility, resistance to heat aging and high damping. The spacing between the shields also determines the magnetic shielding factor.

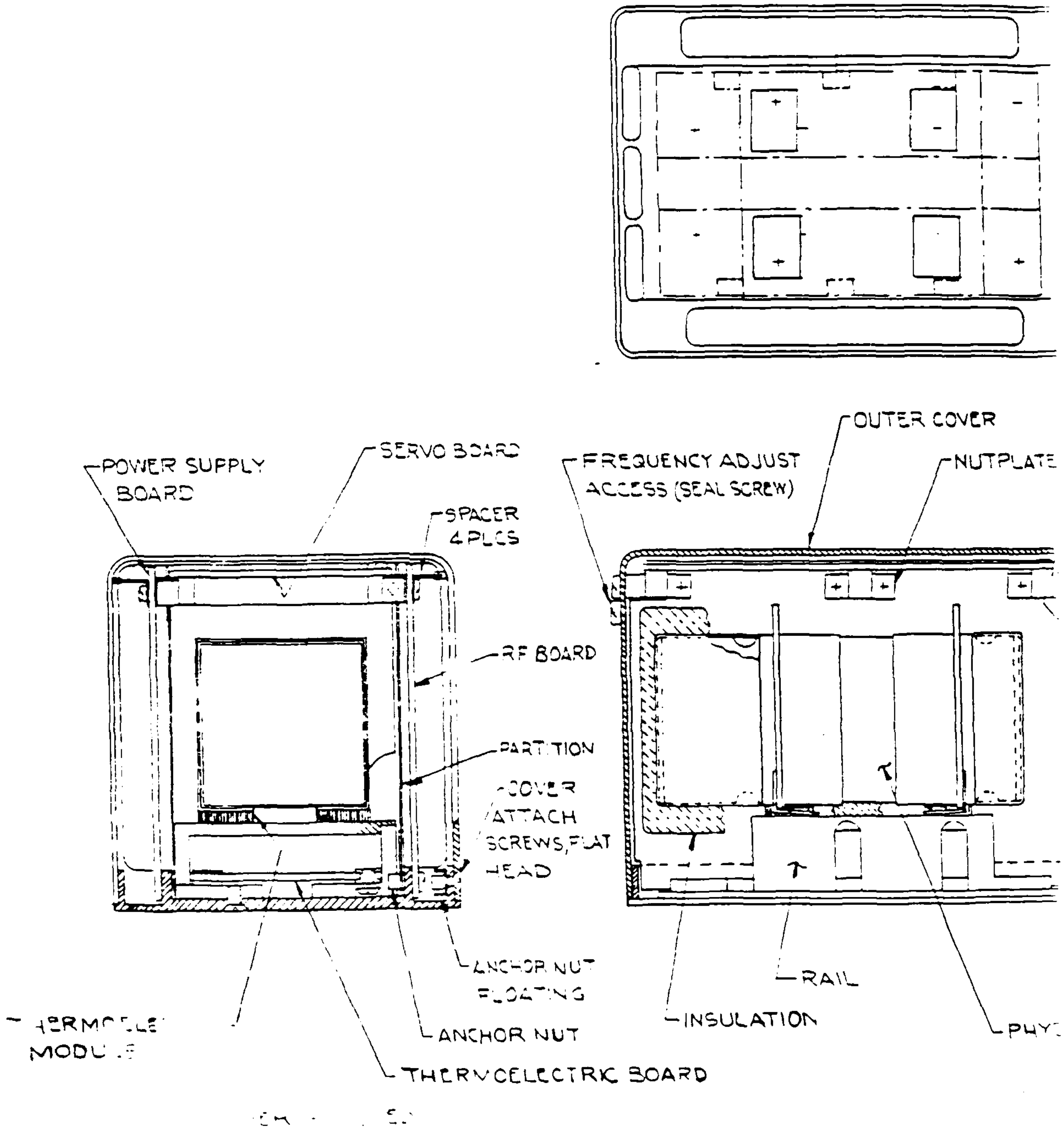
A thermoelectric cooling assembly is located between the physics package and the baseplate. It consists of four thermoelectric cooling modules and the thermoelectric controller board. The square magnetic shield is mounted on these thermoelectric modules to allow high baseplate temperature operation. The modules are located at the resilient mounts to provide mechanical support and to reduce temperature gradients. The shield is surrounded by thermal insulation to reduce the heat load that must be pumped. The heat load on each module is low to reduce temperature drops across joints and to achieve a high coefficient of performance.

The main rf, servo and power boards are located on the remaining three sides of the physics package. The servo board, which has very low power dissipation, is located at the top. The rf and power boards are located on the sides. These three boards are attached to the main structure and each other for support especially to limit flexure during vibration.

A smaller board at the front holds the input power filters and one at the bottom holds the thermoelectric controller circuit. These boards, which are mounted to the main structure, contain most of the components that are relatively massive or have high heat dissipation and therefore have suitable heat sinking and support. Printed circuit boards are conformally coated to prevent degradation due to surface contamination, to increase heat conduction, to give support for components and leads and to increase board damping. Precautions are taken to protect fragile components and avoid thermal stresses due to entrapment of coating under components.

Special attention has been given to the details of design and construction and the selection of materials in order to meet the stringent environmental conditions, especially temperature and vibration. Soft solder joints alone are not used for structural loads except for mounting very lightweight components. Component leads have strain relief and threaded fasteners have locking features. Stranded hook-up wire is used for its greater vibration resistance and lower sensitivity to nicks. Wires are laced and cables clamped for support. Electrical insulation is protected from sharp corners and edges which could cut, abrade or cause flow of the insulator.

Overall, this arrangement provides a logical, modular and accessible package. It is fully compliant with Revision E of the TRFS specifications



OUTER COVER
SERVO BOARD
POWER SUPPLY BOARD
FREQUENCY ADJUST ACCESS (SEAL SCREW)
NUTPLATE
SPACER 4 PLCS
RF BOARD
PARTITION
COVER ATTACH SCREWS, FLAT HEAD
ANCHOR NUT
RAIL
INSULATION
ANCHOR NUT
THERMOELECTRIC BOARD

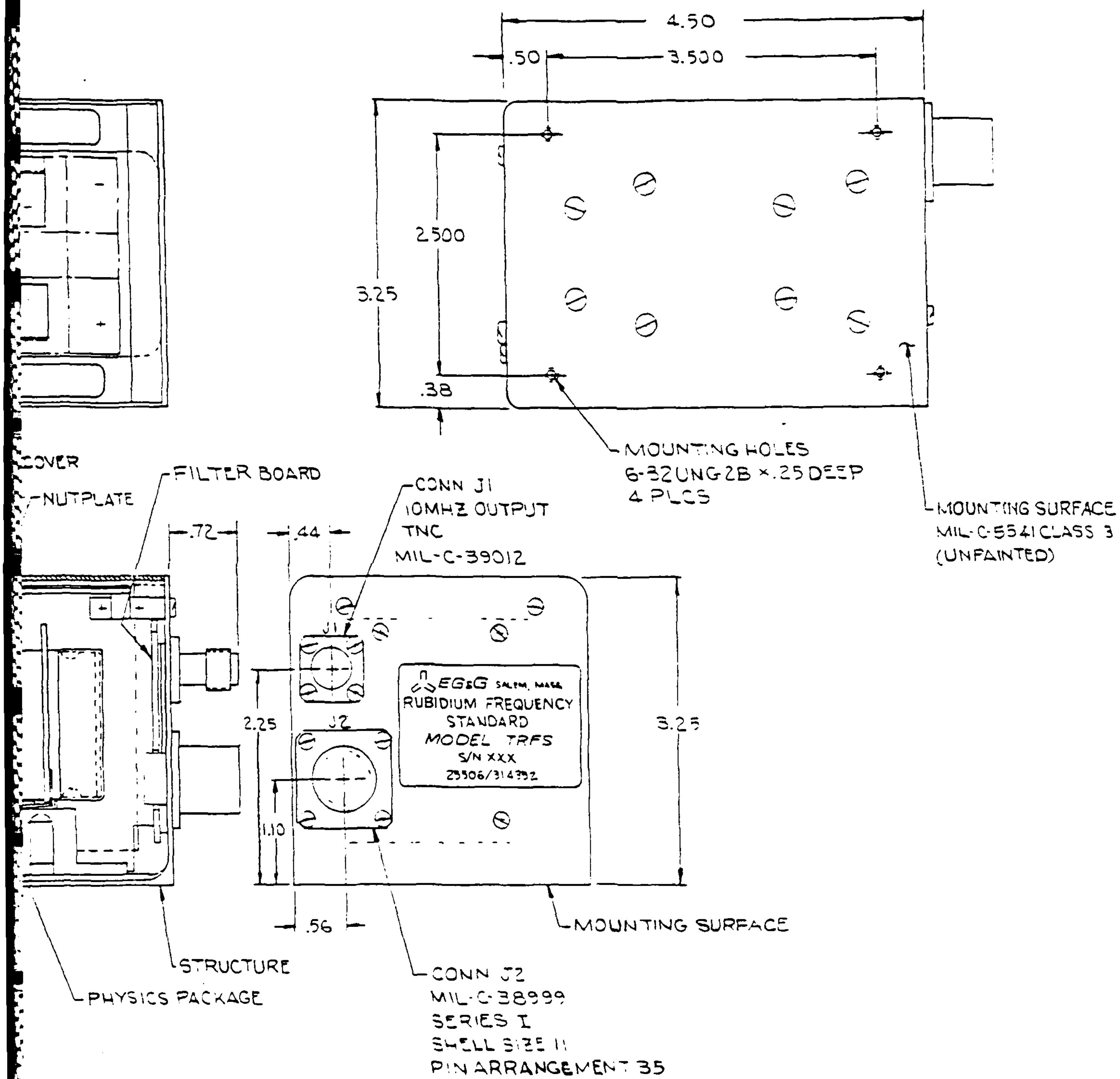



Figure 3.2. TRFS Packaging.



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as described in paragraph 3.2.2 and Figure 2 of Appendix A and in the outline drawing of Figure 1.2 of this report.

3.3 Physics Package Section. The physics package section of the TRFS includes, besides the Rb physics package itself, the associated lamp exciter, microwave multiplier and preamplifier circuits.

3.3.1 Physics Package. The heart of the TRFS is the physics package. It combines good performance with ultra-miniature size by using a dielectrically loaded cavity that contains separate filter and absorption cells. The basic physics package structure is shown in Figure 3.3.1.1, and the various elements of the physics package are shown in Figure 3.3.1.2.

Miniaturization of the lamp assembly was accomplished by using a very small rubidium lamp excited by an rf power oscillator built into the lamp oven. This gives excellent lamp starting and running, good rf shielding, temperature control of the lamp exciter, and high thermal efficiency since the exciter dissipation helps to heat the lamp oven. The lamp oven operates at a temperature of about +115$^{o}$C.

Miniaturization of the TE111 microwave cavity was obtained, paradoxically, by putting more into it; specifically, by locating a filter cell inside the cavity. This discrete filter cell improves performance by allowing independent nulling of the light shift. This gives good spatial homogeneity in the absorption cell and results in a low rf power coefficient. Locating the filter cell inside the cavity allows cancellation of the filter cell temperature coefficient by that of the absorption cell. Both the lamp and cavity ovens have a nominally zero temperature coefficient. The resulting increase in the amount of the glass dielectric in the cavity also reduces its size. A further advantage is that the filter and absorption cells become physically shorter, which is desirable for optimum signal at a high operating temperature. The cavity also contains a step-recovery diode microwave multiplier. The cavity oven operates at a temperature of about +75$^{o}$C.

The physics package includes two lenses in the optical path. The

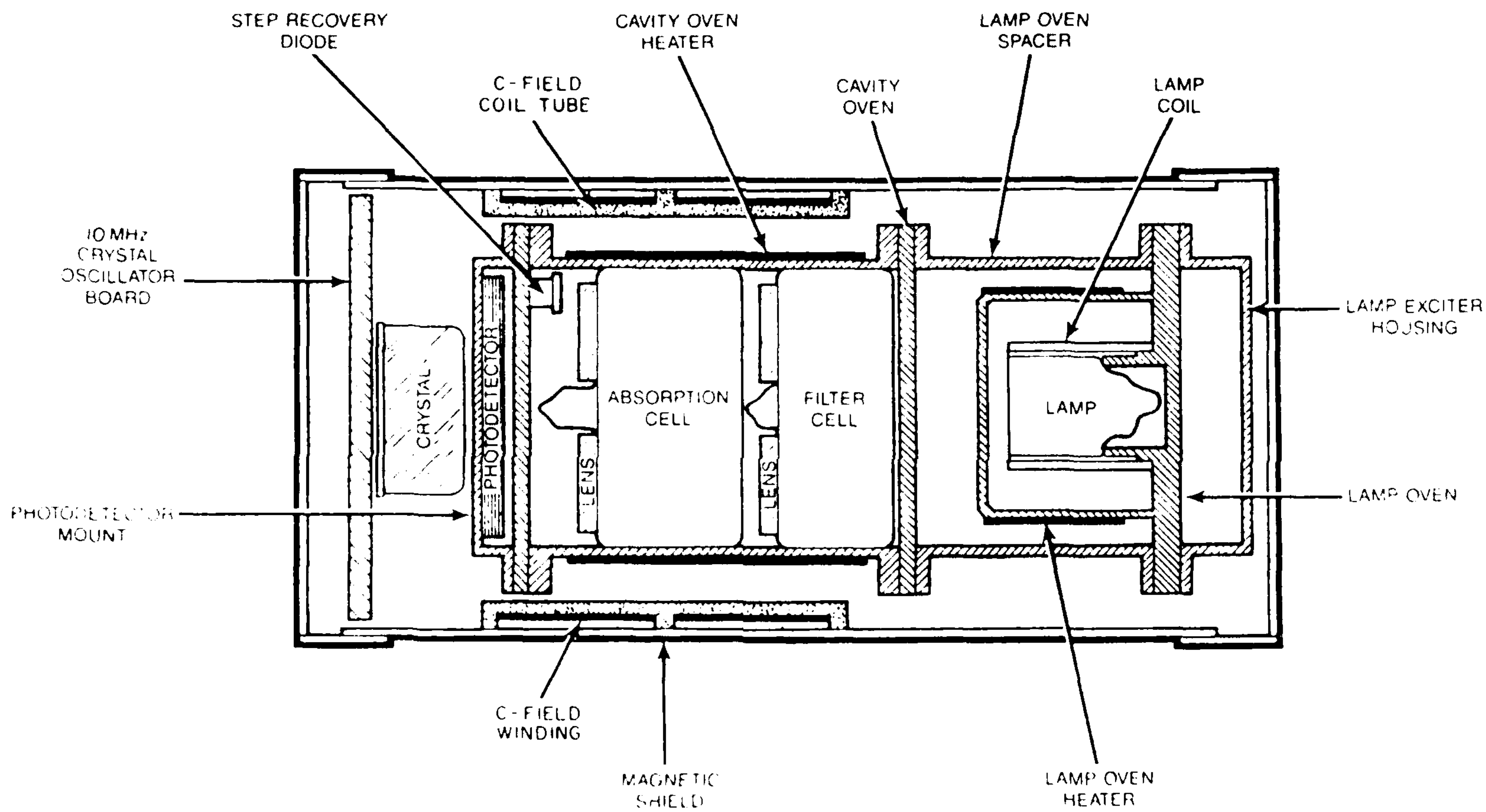



Figure 3.3.1.1. Physics Package Cross-section.

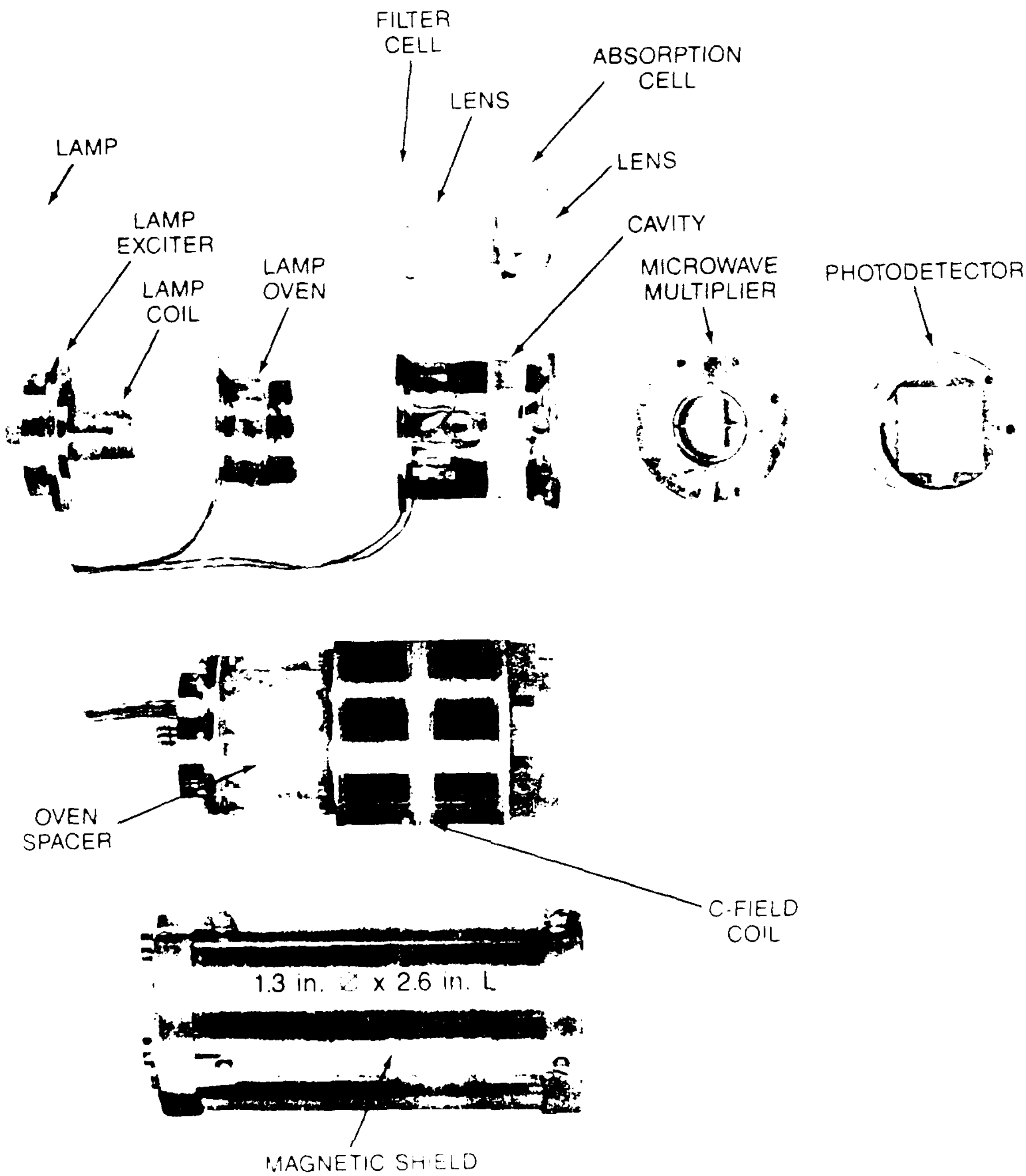



Figure 3.[illegible] Physics Package Parts.

first, located in front of the absorption cell, collimates the lamp output to give a uniform light intensity distribution. The second lens, located behind the absorption cell, focuses the light on the photodetector to give good collection efficiency. The photodetector is a custom EG&G device having low noise and high radiation hardness.

The C-field coil is wound in two sections to provide good C-field uniformity, which helps to ensure line homogeneity and minimizes rf power sensitivity.

A non-metallic spacer rigidly connects the lamp and cavity ovens for ruggedness and low vibration sensitivity with low heat transfer between the ovens. The physics package is double-shielded for low magnetic sensitivity and is supported by silicone rubber mounts that provide shock and vibration isolation.

3.3.2 Lamp Exciter. The rubidium lamp is excited with an rf power of about 0.5 watt at 105 MHz. This energy is applied to the lamp by operating it inside the field of an rf coil which excites optical emissions from an ionized plasma. The lamp provides the Rb resonance radiation required for optical pumping.

The lamp exciter circuit (see Figure 3.3.2) is a Colpitts rf power oscillator whose frequency is determined primarily by the series tuned L1-C1 lamp coil network. The circuit is packaged as part of the lamp assembly in the physics package and operates from the -15 V supply. This assembly provides a compact, well-shielded, and temperature-controlled environment.

Lamp exciter operation is stabilized by a current regulator circuit located on the preamplifier board. That circuit controls the lamp exciter dc bias, boosting the exciter output for lamp starting and stabilizing it during normal operation.

3.3.3 Microwave Multiplier. The step-recovery diode (SRD) microwave multiplier is incorporated into the temperature-controlled cavity. Its

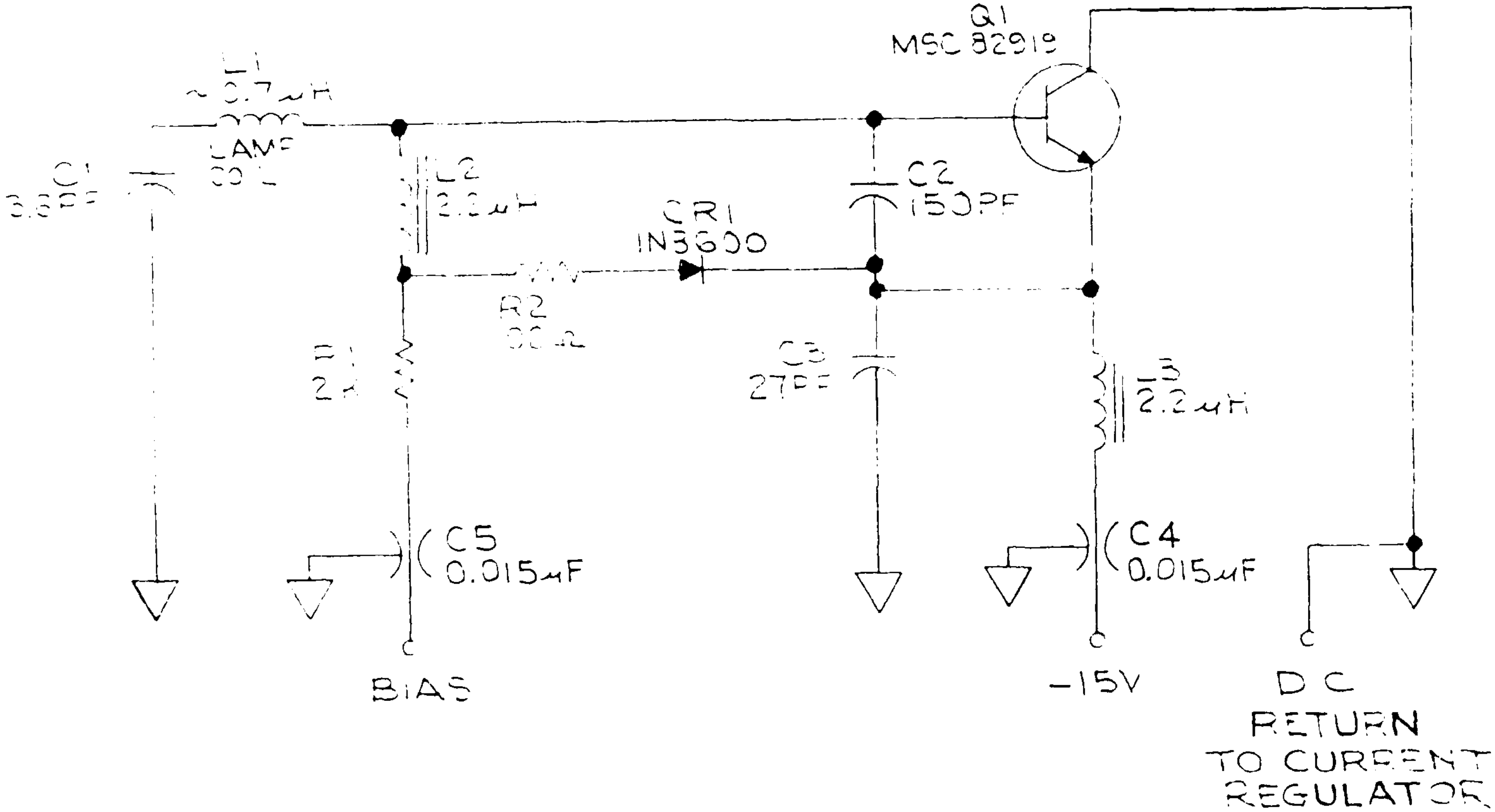



Figure 3.3.2. Lamp Exciter Schematic.

design is both simple and efficient since it works as a straight X76 multiplier (see Figure 3.3.3). It is driven by a +20 dBm signal at about 90 MHz and produces about 100 uW at the rubidium resonance frequency of approximately 6835 MHz.

3.3.4 Preamplifier. The preamplifier circuit is on a small board located between the magnetic shield covers at the photodetector end of the physics package. It converts the photodetector current to a voltage which drives the servo-amplifier. The preamplifier board also contains the lamp exciter current regulator circuit. These circuits are shown in Figure 3.3.4.

The preamplifier circuit has a dc transresistance of 200 KΩ, so a nominal 25 μA dc photodetector current produces a 5 V dc output which serves to monitor the rubidium lamp. The preamplifier has an ac transimpedance of a 5 MΩ which is broadly peaked at the servo-modulation frequency of about 800 Hz. The normal second harmonic recovered signal is about 50 mV rms at the preamplifier output.

The current regulator circuit stabilizes the lamp exciter dc current at 100 mA under normal operation, and at 200 mA for starting by sensing the voltage drop across R11 in the dc return lead.

3.4 10 MHz VCXO Section. The 10 MHz VCXO is located inside the physics package assembly. It consists of a voltage-controlled crystal oscillator (VCXO) that is locked by the servo-amplifier to the rubidium resonance frequency and produces the output signal from the TRFS. The VCXO uses a 10 MHz 3rd overtone mode SC-cut crystal in a TO-8 nonmagnetic enclosure. This crystal type is chosen for its small size, ruggedness, fast warm-up, and low vibration sensitivity. It is mounted on the ~1.25 inch diameter VCXO board that is attached to the photodetector end of the microwave cavity and thereby shares the 75°C stabilized thermal environment of the cavity oven.

The 10 MHz VCXO circuit is shown in the schematic diagram of Figure 3.4. It consists of a Colpitts oscillator circuit, a common-base tuned buffer amplifier, and an ALC detector/amplifier. A transistor array is used for all the active devices. The oscillator and buffer stages form a cascade

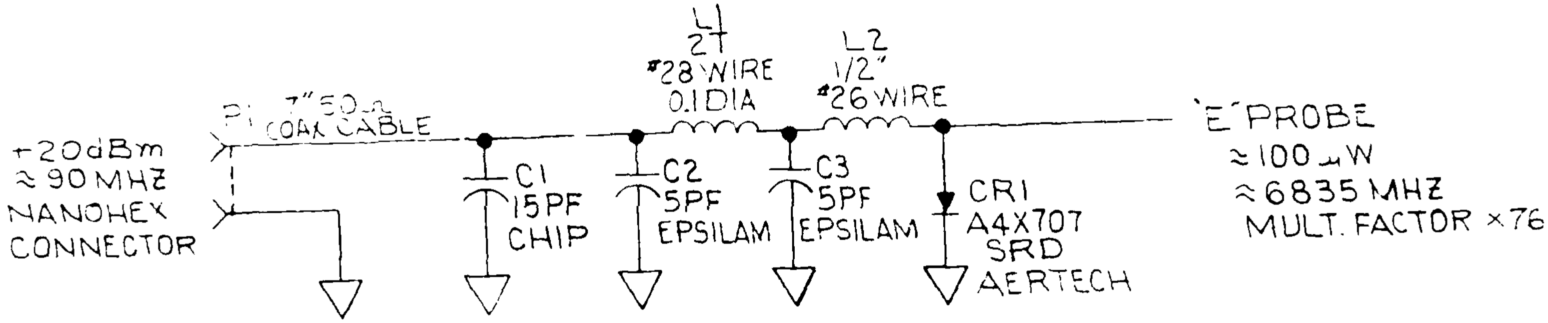



Figure 3.3.3. Microwave Multiplier Schematic.

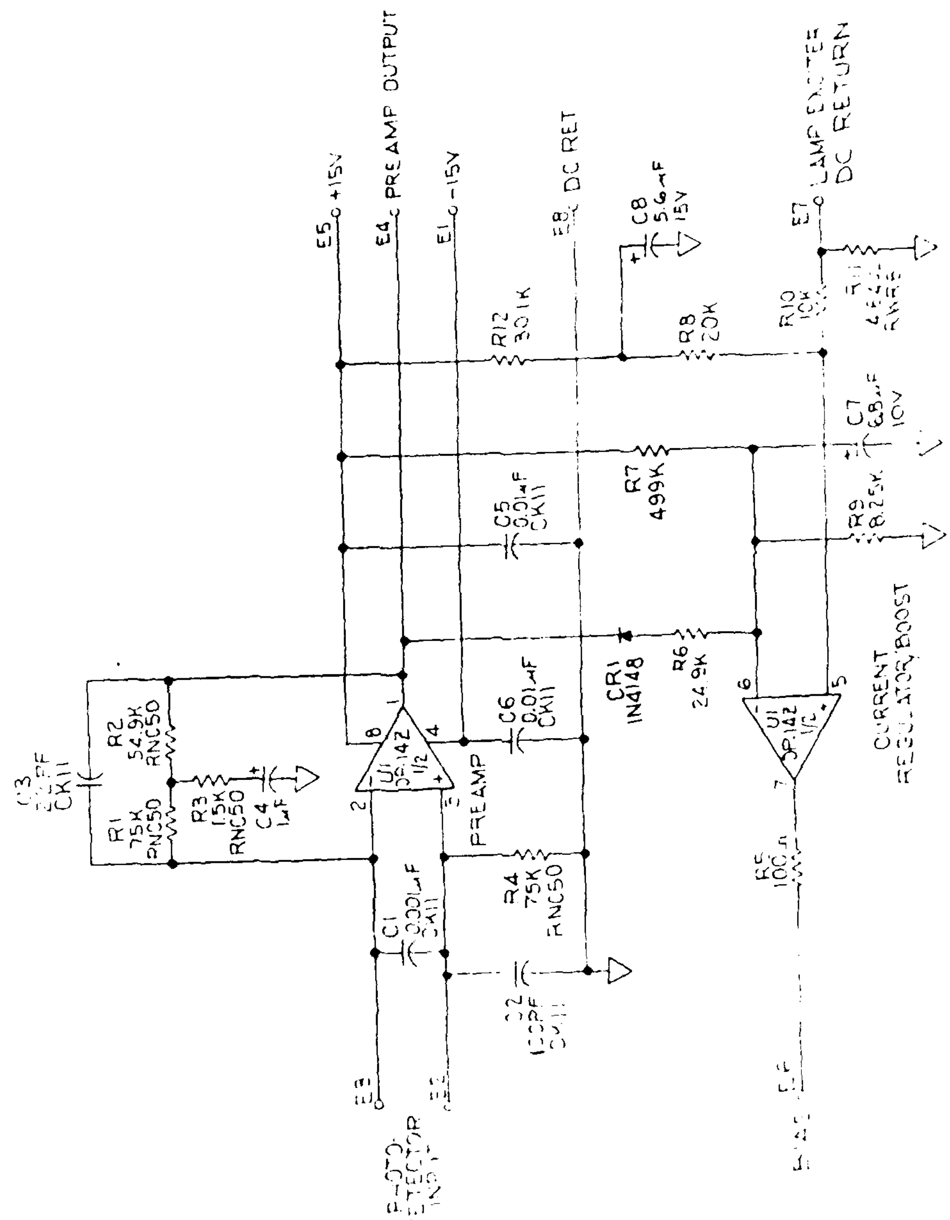



Figure 3.3.4. Preamplifier Schematic.

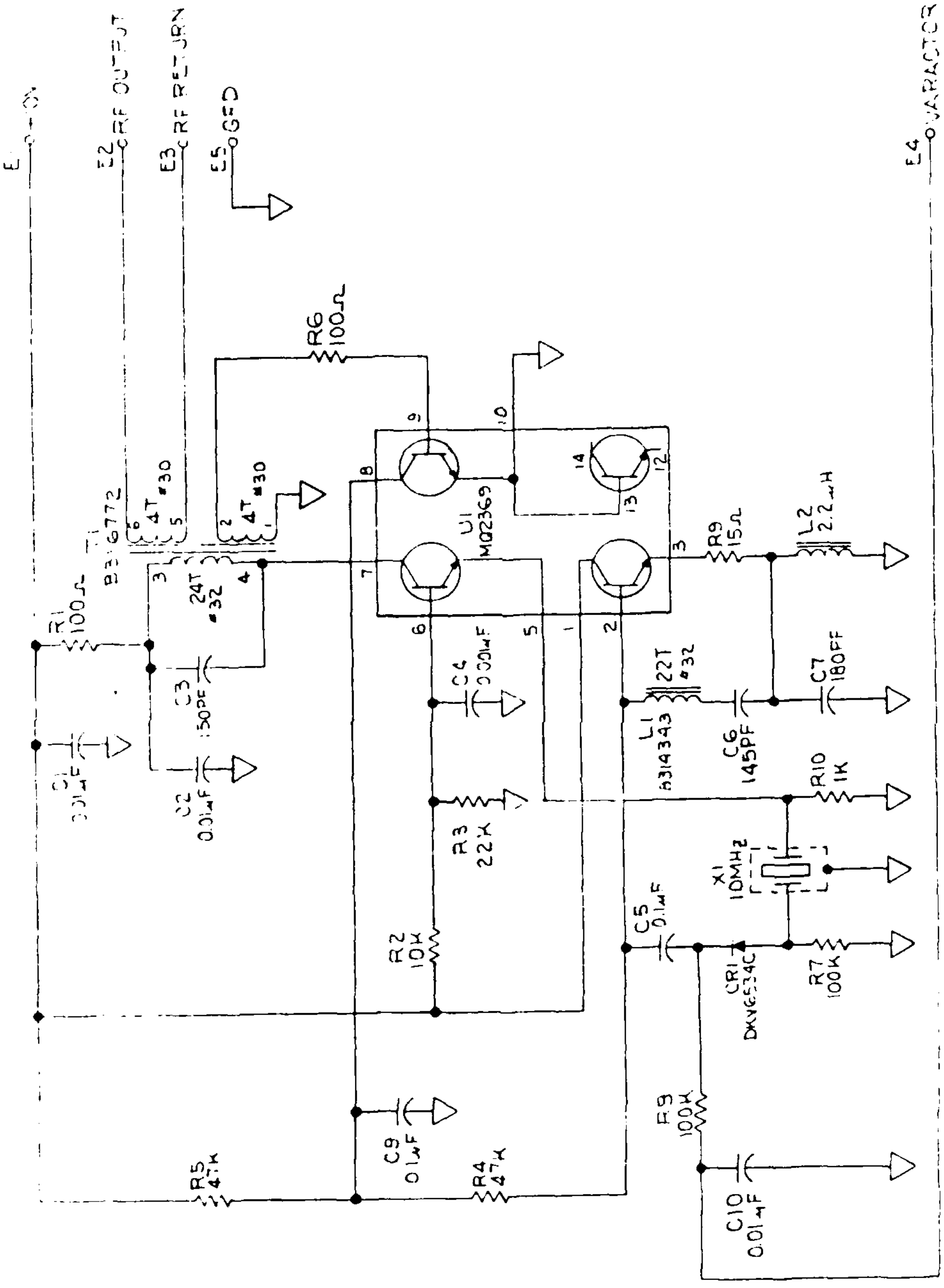



Figure 3.4. 10 MHz VCXO Schematic.

configuration. The crystal network is conventional except for the L1-C6 branch, which suppresses the unwanted "B"-mode oscillation about 11 MHz. A varactor diode is used to provide voltage control of the oscillator frequency and has a tuning range of about 5 ppm, sufficient to correct for VCXO drift for the life of the TRFS (see Section 4.5). The ALC transistor detects the VCXO output signal and adjusts the dc bias applied to the oscillator stage so as to maintain a constant output level.

3.5 RF Section. The rf section of the TRFS consists of the synthesizer and amplifier circuits on the rf board that process the 10 MHz VCXO signal to excite the physics package and produce the TRFS output.

A block diagram of the synthesizer is shown in Figure 3.5.1. The 10 MHz VCXO frequency is multiplied by a factor of 76(9-1/143) to the Rb hyperfine resonant frequency of 6834.685316 MHz. Synthesis of 10(9-1/143) ≈ 89.93007 MHz is accomplished by a phase-locked crystal oscillator which drives the x76 SRD microwave multiplier in the Rb physics package.

The rf board circuits are shown in Figure 3.5.2. The output from the 10 MHz VCXO is converted to a TTL signal that drives the synthesizer and TRFS output amplifier. A portion of the ~90 MHz crystal oscillator output, after amplification, is applied to a harmonic mixer whose other input is a 10 MHz TTL signal. The mixer produces an output at the ~70 kHz difference between the ninth harmonic of 10 MHz and the ~90 MHz crystal oscillator frequency. This signal is band-pass filtered and drives an exclusive-OR CMOS phase detector via a comparator. The other input of the phase detector is driven via a level translator from the ~70 kHz reference signal which is obtained from the 10 MHz TTL signal after division by 143.

The phase detector output is low-pass filtered and integrated and applied as the crystal oscillator control voltage. The overall configuration is that of phaselock loop and it avoids the bulky and critical tuned circuits of a conventional synthesizer-multiplier. Wide loop bandwidth (~5 kHz) is obtained by using translation rather than division inside the loop. This also results in low phase noise since the loop is essentially

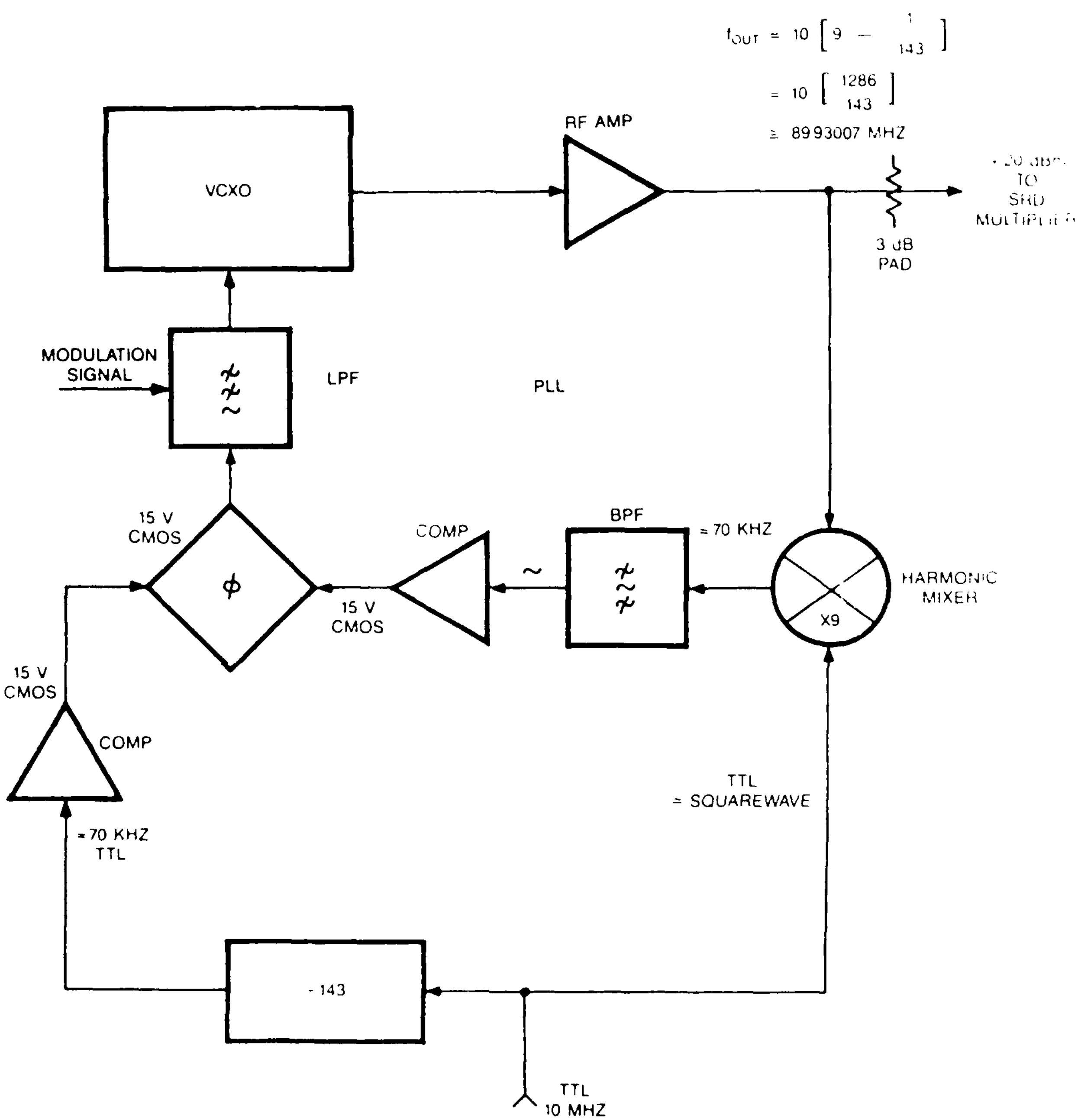



Figure 3.5.1. Synthesizer Block Diagram.

an X9 multiplier and no significant noise is contributed by the ~70 kHz reference. Wide loop bandwidth is necessary to avoid vibrational noise and to permit the application of servo modulation.

3.6 Servo Section. The servo section of the TRFS consists of the servo-amplifier board which processes the Rb discriminator signal.

The TRFS servo-amplifier uses a cascaded detector arrangement wherein the fundamental error signal passes through the second harmonic detector before reaching the fundamental detector, as shown in the block diagram of Figure 3.6.1. This has the advantage of requiring less hardware. The op amp associated with the second harmonic detector also provides gain for tne fundamental signal. The large amplitude second harmonic signal is shifted to the fourth harmonic ahead of the fundamental detector, making it possible to obtain sufficient dynamic range without a bulky and critical notch filter.

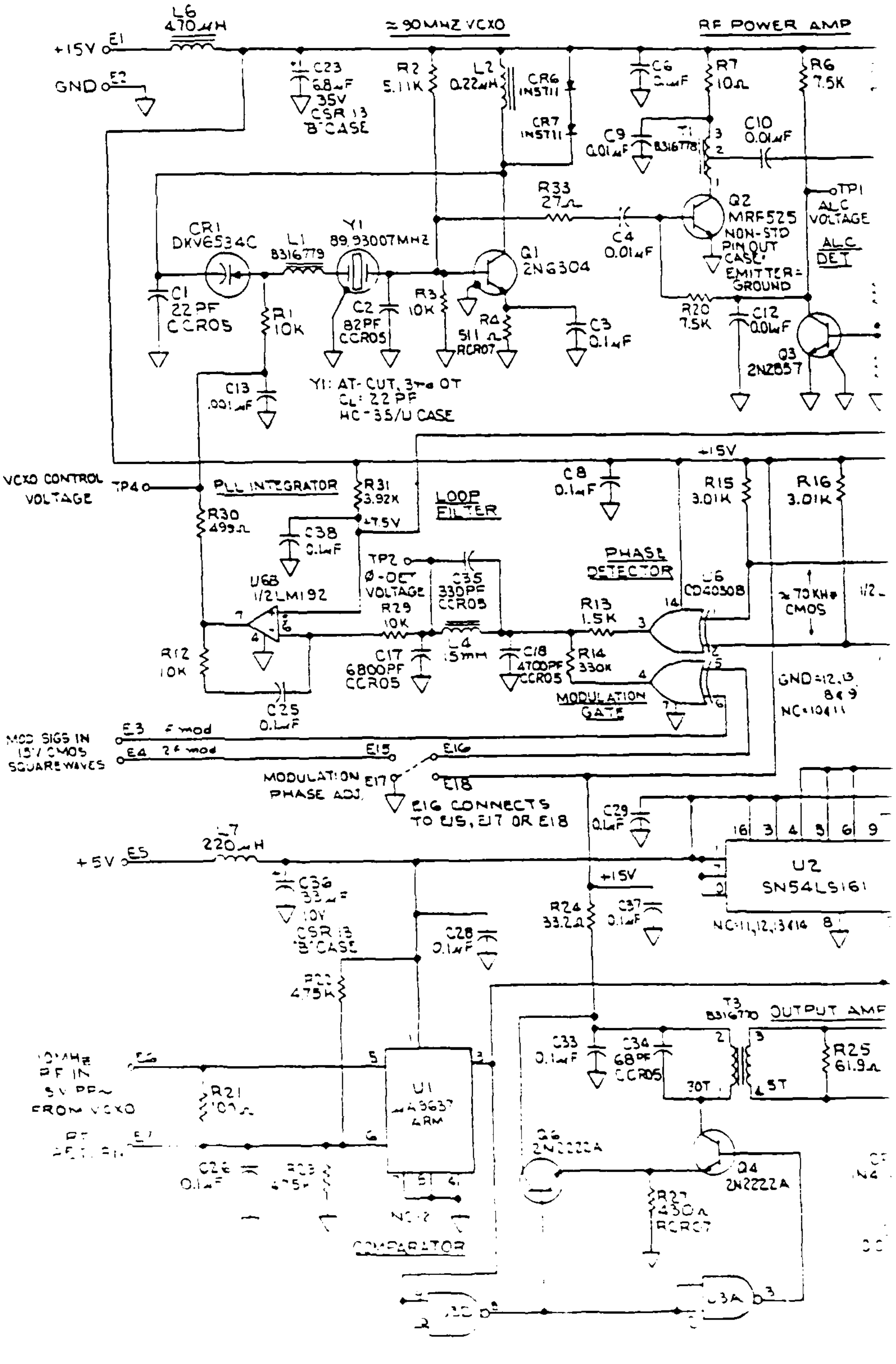
The two detectors are driven by reference signals generated by the modulation rate generator and detector logic, which also provides a modulation signal to the rf board.

The second harmonic detector dc output drives a comparator that indicates lock of the Rb servo. The lock signal is combined with a level detector at the 10 MHz TRFS output to form the built-in-test (BIT) signal. A sweep circuit is used to insure lock acquisition.

The circuits of the servo-amplifier are shown in the schematic diagram of Figure 3.6.2.

3.7 Power Section. The TRFS power section consists of the power and thermoelectric controller boards and the dc input filters.

3.7.1 Power Board. The TRFS power board contains three circuits, a power supply and two temperature controllers. The power supply dc/dc converter produces outputs of +6 V and ±16V from the +26 V dc electronic power input. The +6 V output is regulated to +5 V and supplies the digital circuits.



≈90 MHZ VCXO
RF POWER AMP
+15V E1
GND E2
L6 470µH
C23 6.8µF 35V CSR 13 'B' CASE
R2 5.11K
L2 0.22µH
CR6 IN5711
CR7 IN5711
C6 .1µF
R7 10Ω
R6 7.5K
C9 0.01µF
T1 B316778
C10 0.01µF
R33 27Ω
TP1 ALC VOLTAGE
ALC DET
Q2 MRF525 NON-STD PIN OUT CASE EMITTER=GROUND
C4 0.01µF
CR1 DKV6534C
L1 B316779
Y1 89.93007MHZ
Q1 2N6304
C1 22PF CCR05
R1 10K
C2 82PF CCR05
R3 10K
R4 511Ω RCR07
C3 0.1µF
R20 7.5K
C12 0.01µF
Q3 2N2857
C13 .001µF
Y1: AT-CUT, 3rd OT
CL: 22 PF
HC-35/U CASE
+15V
VCXO CONTROL VOLTAGE TP4
PLL INTEGRATOR
R31 3.92K
+7.5V
LOOP FILTER
C8 0.1µF
R15 3.01K
R16 3.01K
R30 499Ω
C38 0.1µF
TP2 Ø-DET VOLTAGE
C35 330PF CCR05
PHASE DETECTOR
U6 CD4030B
≈70KHz CMOS
U6B 1/2 LM192
R29 10K
L4 .5mH
R13 1.5K
R12 10K
C17 6800PF CCR05
C18 4700PF CCR05
R14 330K
MODULATION GATE
GND=12,13, 8 & 9
NC=10 & 11
C25 0.1µF
MOD SIGS IN 15V CMOS SQUARE WAVES
E3 f mod
E4 2f mod
E15
E16
MODULATION PHASE ADJ. E17
E18
E16 CONNECTS TO E15, E17 OR E18
C29 0.1µF
U2 SN54LS161
NC=11,12,13 & 14
+5V E5
L7 220µH
C36 33µF 10V CSR 13 'B' CASE
+15V
R24 33.2Ω
C37 0.1µF
C28 0.1µF
R22 475K
T3 B316770
OUTPUT AMP
C33 0.1µF
C34 68PF CCR05
30T
5T
R25 61.9Ω
10 MHz RF IN 5V P-P FROM VCXO
E6
R21 100Ω
U1 µA3637 ARM
E7
C26 0.1µF
R23 475K
Q6 2N2222A
Q4 2N2222A
R27 430Ω RCR07
COMPARATOR
U3B
U3A

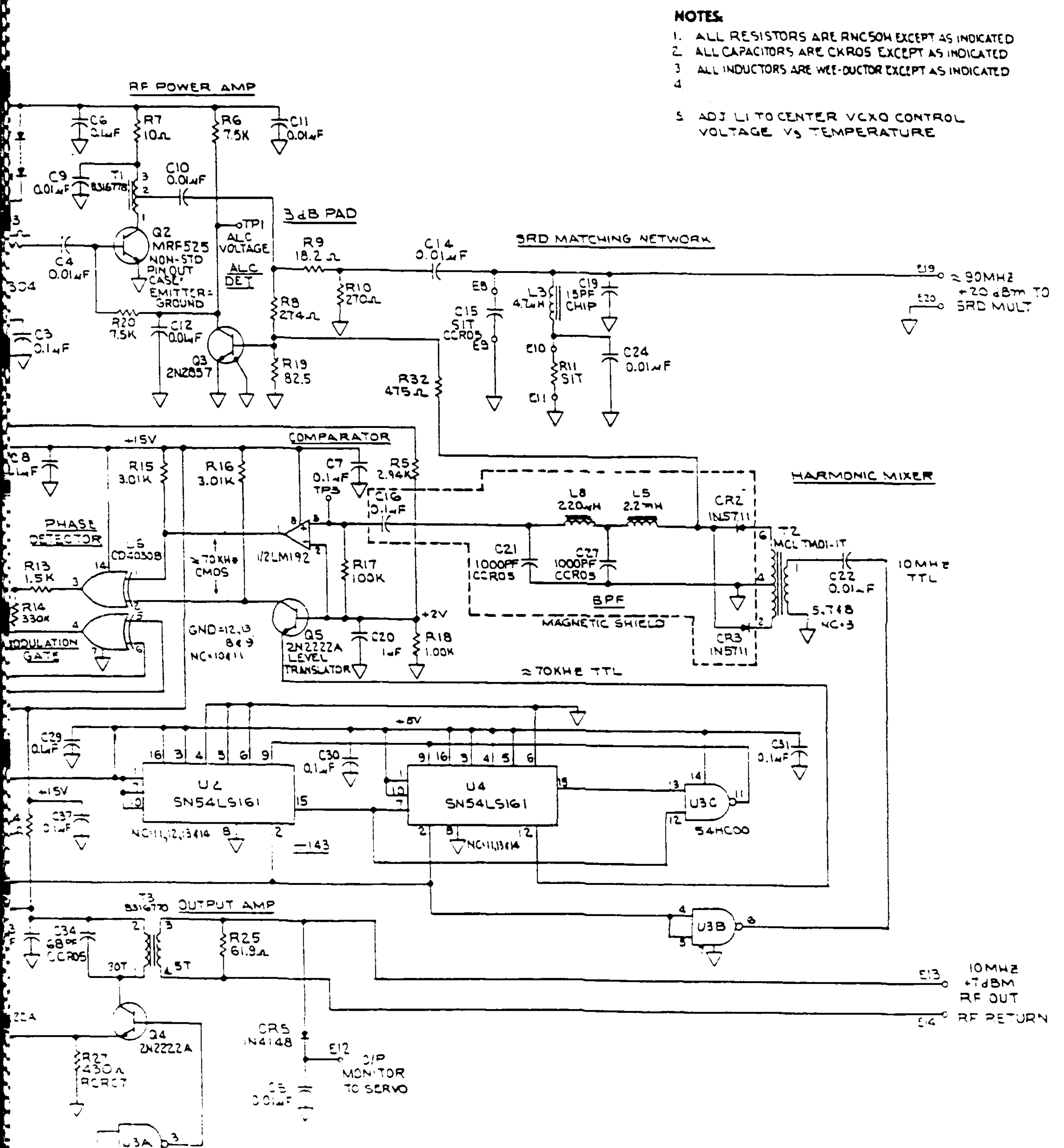



Figure 3.5.2. RF Board Schematic



2

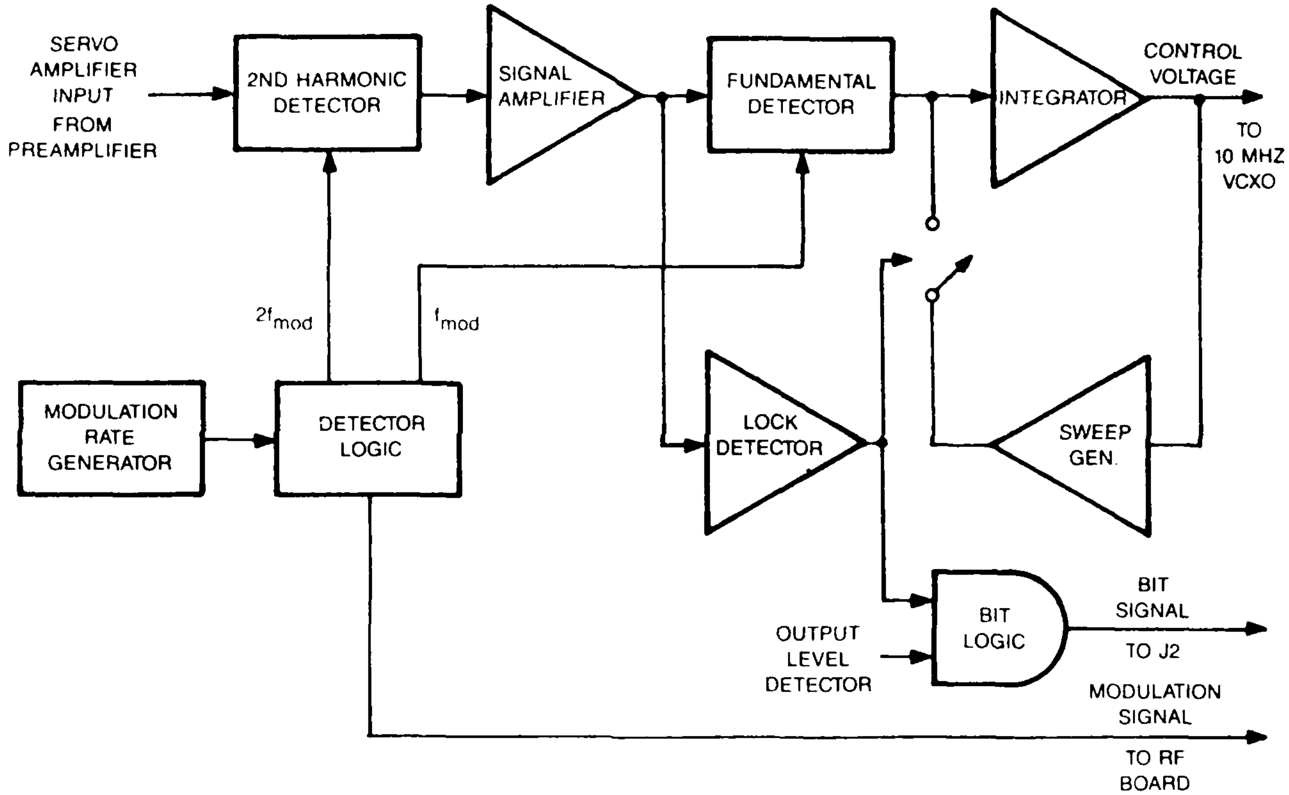



Figure 3.6.1. Servo Amplifier Block Diagram.

The $\pm 16$ V outputs supply the analog circuits via the $\pm 15$ V regulators. Each of these three outputs has a load current of about 100 mA. The two temperature controllers use the +28 V dc heater power input to maintain the lamp and cavity ovens at their proper operating temperatures of about +115$^{o}$C and +75$^{o}$C, respectively. The temperature controllers also contain boost circuits for fast warmup (see Section 4.6). Each of the three efficient switching power circuits operates at about 50 kHz and uses an IC controller device. The dc/dc converter is a flyback configuration while the two temperature controllers are of the series switching type.

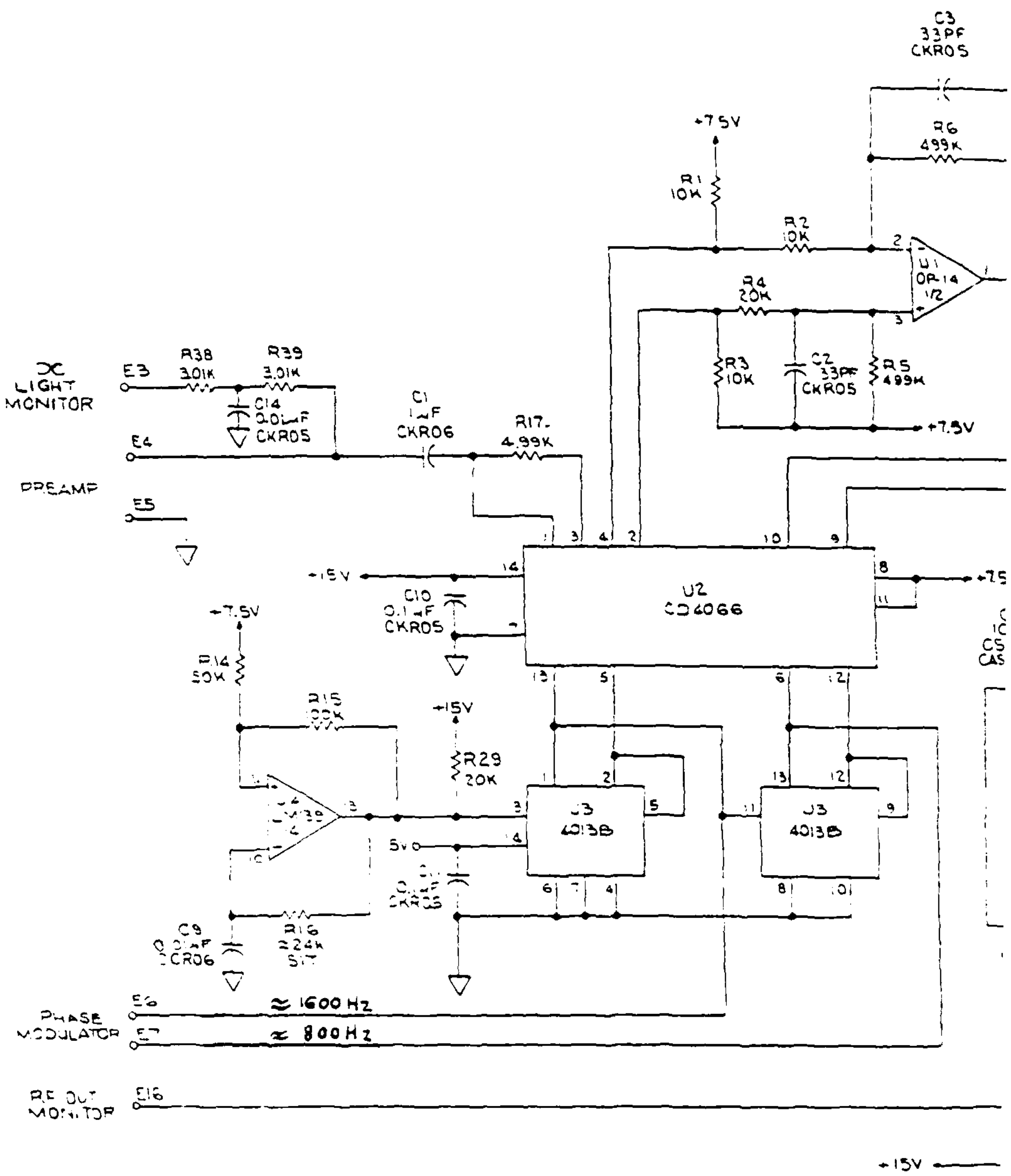
The power board circuit diagram is shown in Figure 3.7.1.

All these power circuits (and those for the thermoelectric cooling controller described in the next section) are designed to withstand the transient requirements of MIL-STD-704 Category B and MIL-STD-1275 as specified for the TRFS (see sections 3.7.3 and 4.3).

3.7.2 Thermoelectric Controller. The thermoelectric controller board holds a switching power supply that generates and controls the power to the thermoelectric cooling modules. This circuit senses the baseplate temperature and operates to cool the physics package as necessary to extend its upper operating temperature limit. The thermoelectric controller circuit diagram is shown in Figure 3.7.2. (See section 4.1 for a more complete description of the TRFS thermoelectric cooling features.)

3.7.3 Input Filter. The TRFS heater and electronic dc input power lines are filtered by the input filter board shown in Figure 3.7.3. These circuits provide transient protection and EMI filtration as described in Section 4.3.

3.8 Interconnections. The interconnections between the various TRFS subassemblies are shown in Figure 3.8.



C3
33PF
CKR05
R6
499K
+7.5V
R1
10K
R2
10K
U1
OP-14
1/2
R4
20K
R3
10K
C2
33PF
CKR05
R5
499K
+7.5V
LIGHT
MONITOR
E3
R38
3.01K
R39
3.01K
C14
0.01μF
CKR05
E4
C1
1μF
CKR06
R17
4.99K
PREAMP
E5
+15V
C10
0.1μF
CKR05
U2
CD4066
+7.5V
R14
50K
R15
100K
+15V
R29
20K
LM339
U3
4013B
U3
4013B
5V
C9
0.01μF
CKR06
R16
224K
SIT
PHASE
MODULATOR
E6
≈ 1600 Hz
E7
≈ 800 Hz
RF OUT
MONITOR
E16
+15V

NOTES:

1. INSTALL 24K RESISTOR AT R16 FOR TEST
2.
3. ALL RESISTORS ARE RNC50 UNLESS OTHERWISE SPECIFIED

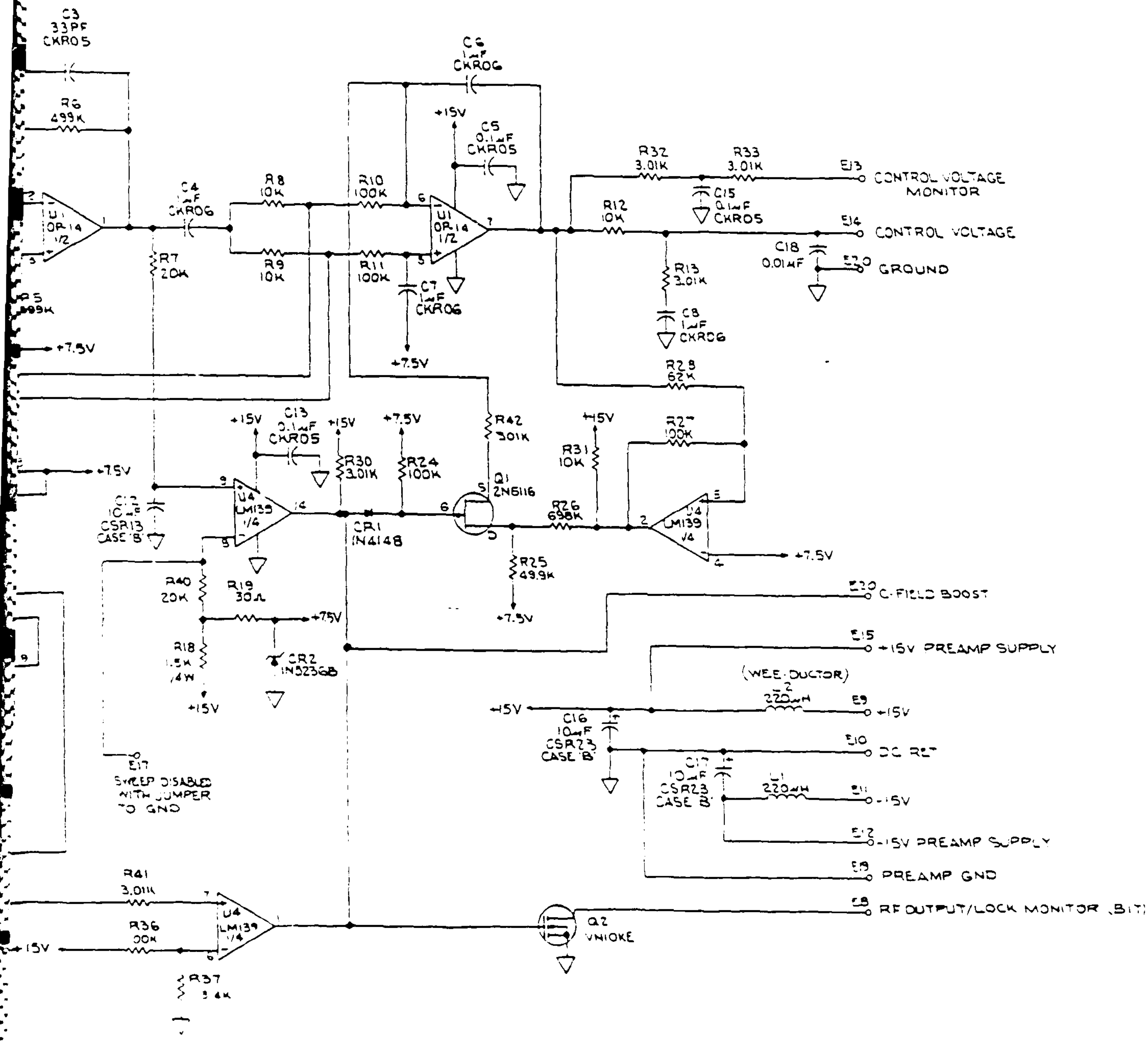
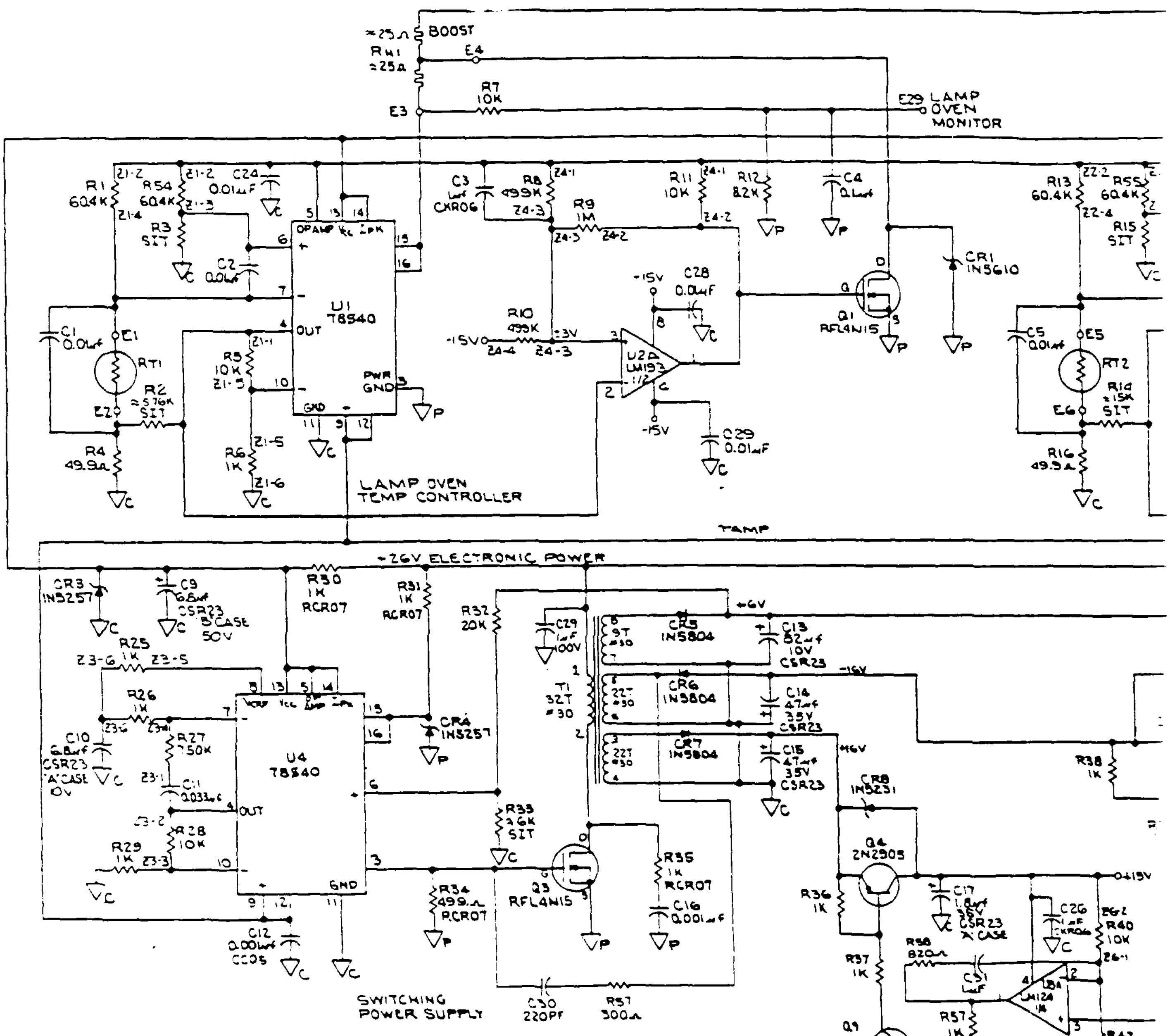



Figure 3.6.2. Servo Amplifier Schematic.



2




NOTES:

1 ALL CAPACITORS ARE CKR06 UNLESS NOTED OTHERWISE

2 ALL RESISTORS ARE 1/8W UNLESS NOTED OTHERWISE

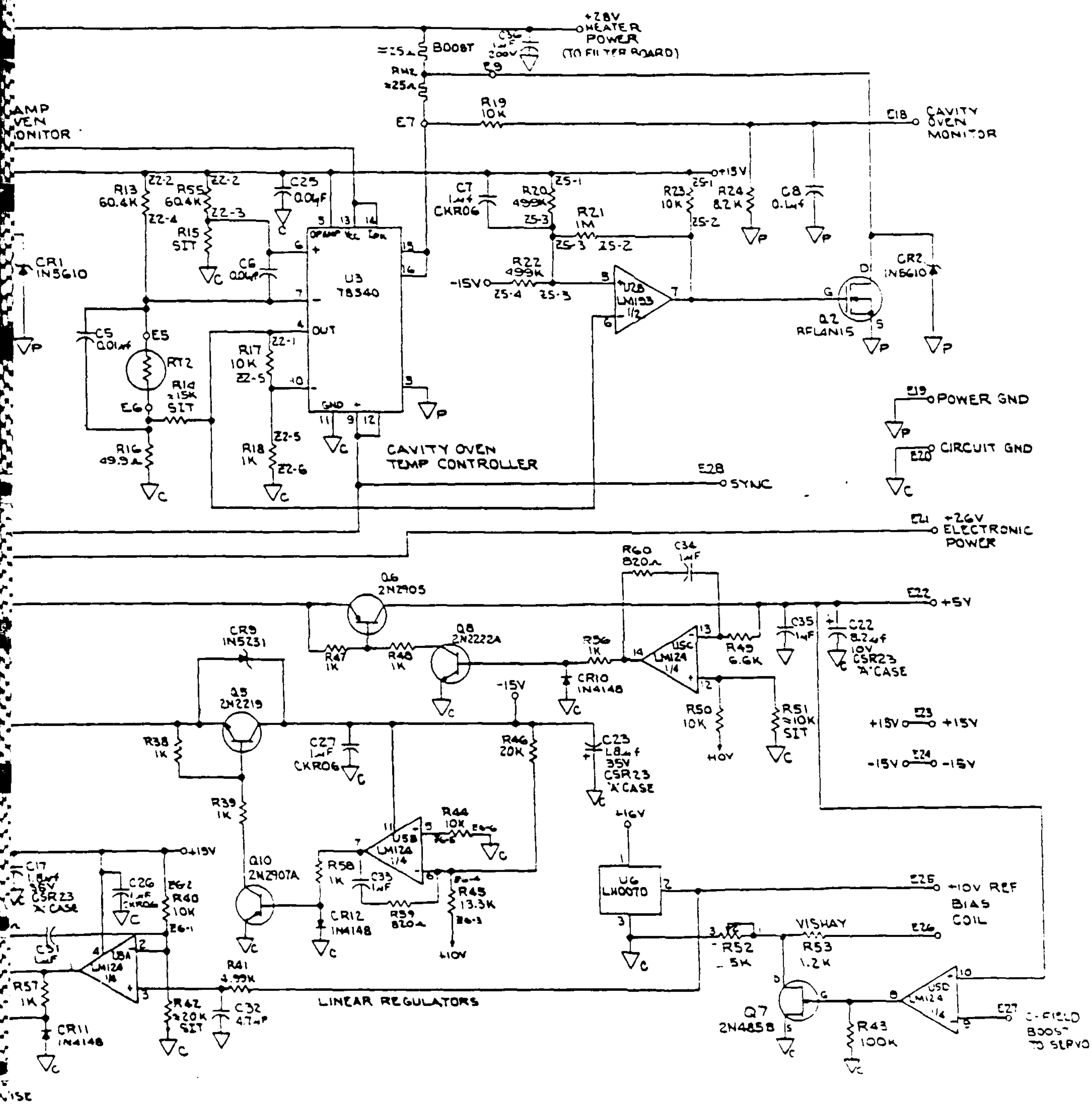
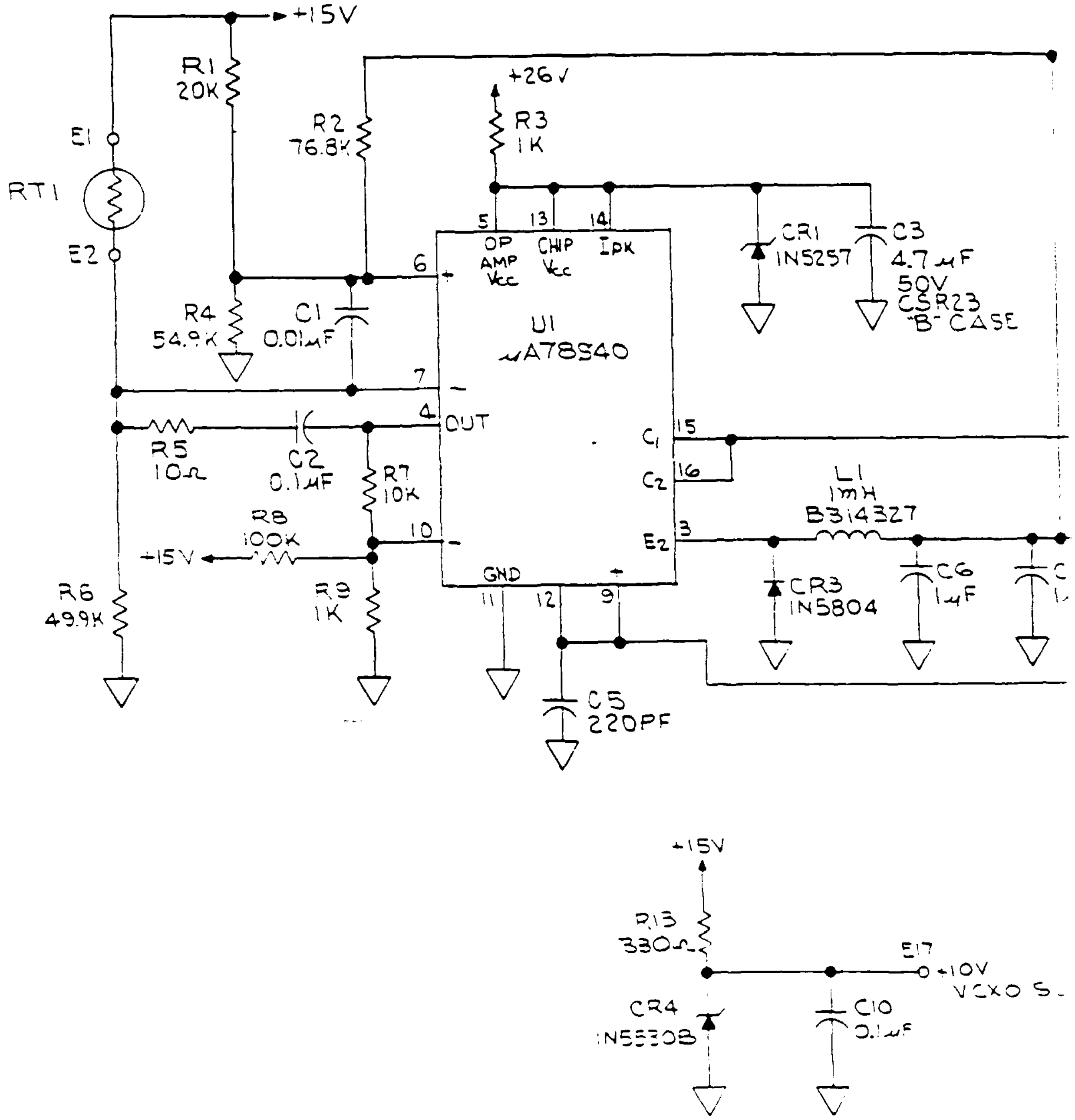



Figure 3.7.1. Power Board Schematic.

2



+15V
R1
20K
+26V
R2
76.8K
R3
1K
E1
RT1
E2
5
13
14
OP AMP Vcc
CHIP Vcc
Ipk
CR1
1N5257
C3
4.7μF
50V
CSR23
"B" CASE
6
R4
54.9K
C1
0.01μF
U1
μA78S40
7
4
OUT
15
C1
C2
16
R5
10Ω
C2
0.1μF
R7
10K
L1
1mH
B314327
R8
100K
10
E2
3
-15V
GND
R6
49.9K
R9
1K
11
12
9
CR3
1N5804
C6
1μF
C5
220PF
+15V
R13
330Ω
E17
+10V
VCXO S
CR4
1N5530B
C10
0.1μF

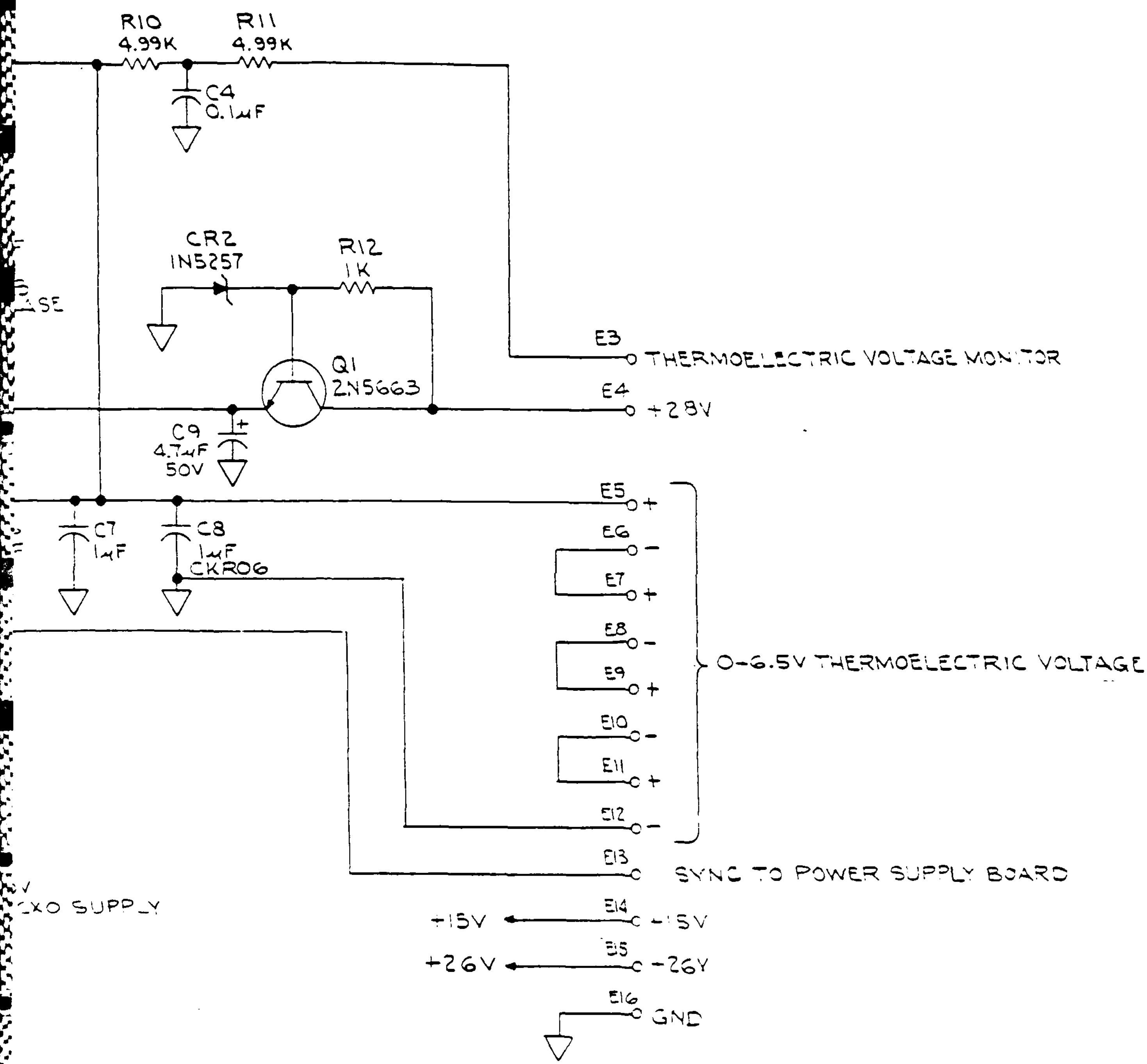



Figure 3.7.2. Thermoelectric Controller Schematic.



2

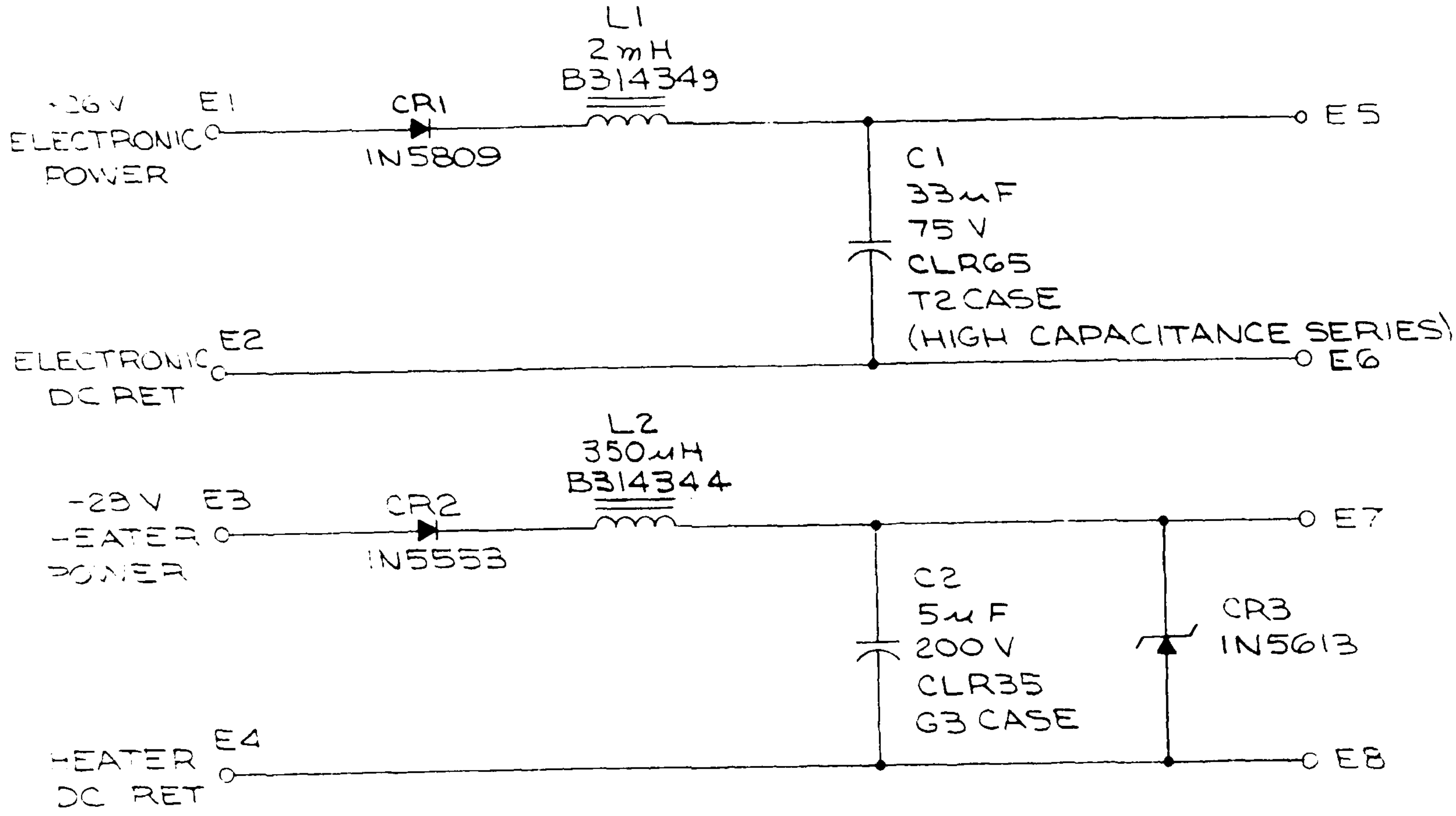
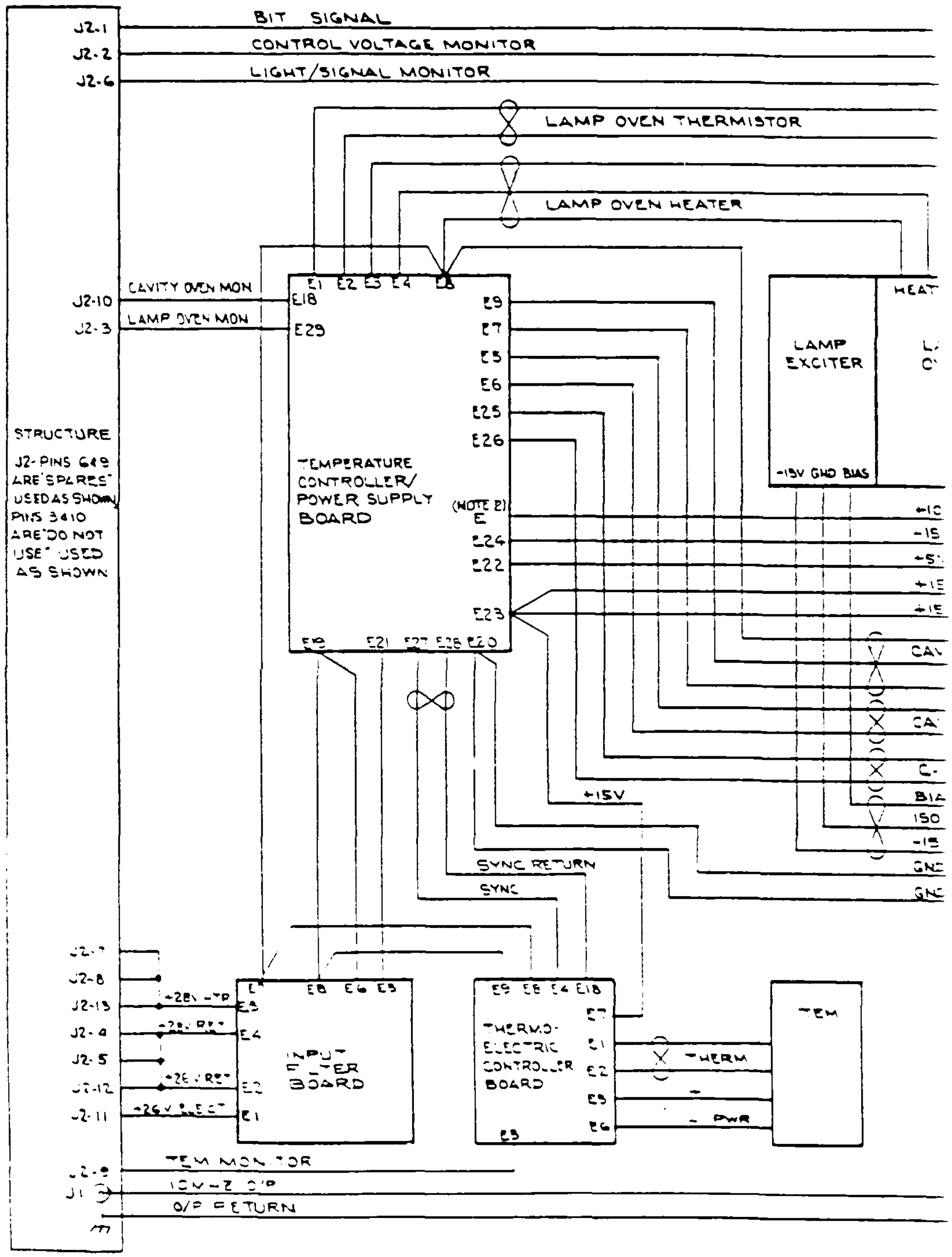



Figure 3.7.3. Input Filter Schematic.



J2-1
J2-2
J2-6
BIT SIGNAL
CONTROL VOLTAGE MONITOR
LIGHT/SIGNAL MONITOR
LAMP OVEN THERMISTOR
LAMP OVEN HEATER
J2-10
J2-3
CAVITY OVEN MON
LAMP OVEN MON
E18
E29
E1 E2 E3 E4
E9
E7
E5
E6
E25
E26
TEMPERATURE CONTROLLER/ POWER SUPPLY BOARD
(NOTE 2) E
E24
E22
E23
E19
E21
E27
E28
E20
LAMP EXCITER
-15V GND BIAS
HEAT
STRUCTURE
J2-PINS 6&9 ARE "SPARES" USED AS SHOWN
PINS 3&10 ARE "DO NOT USE" USED AS SHOWN
+15V
SYNC RETURN
SYNC
J2-7
J2-8
J2-13
J2-4
J2-5
J2-12
J2-11
INPUT FILTER BOARD
E8 E6 E5
E3
E4
E2
E1
THERMO-ELECTRIC CONTROLLER BOARD
E9 E8 E4 E18
E7
E1
E2
E5
E6
THERM
PWR
TEM
TEM MONITOR
O/P RETURN
J2-9
J1

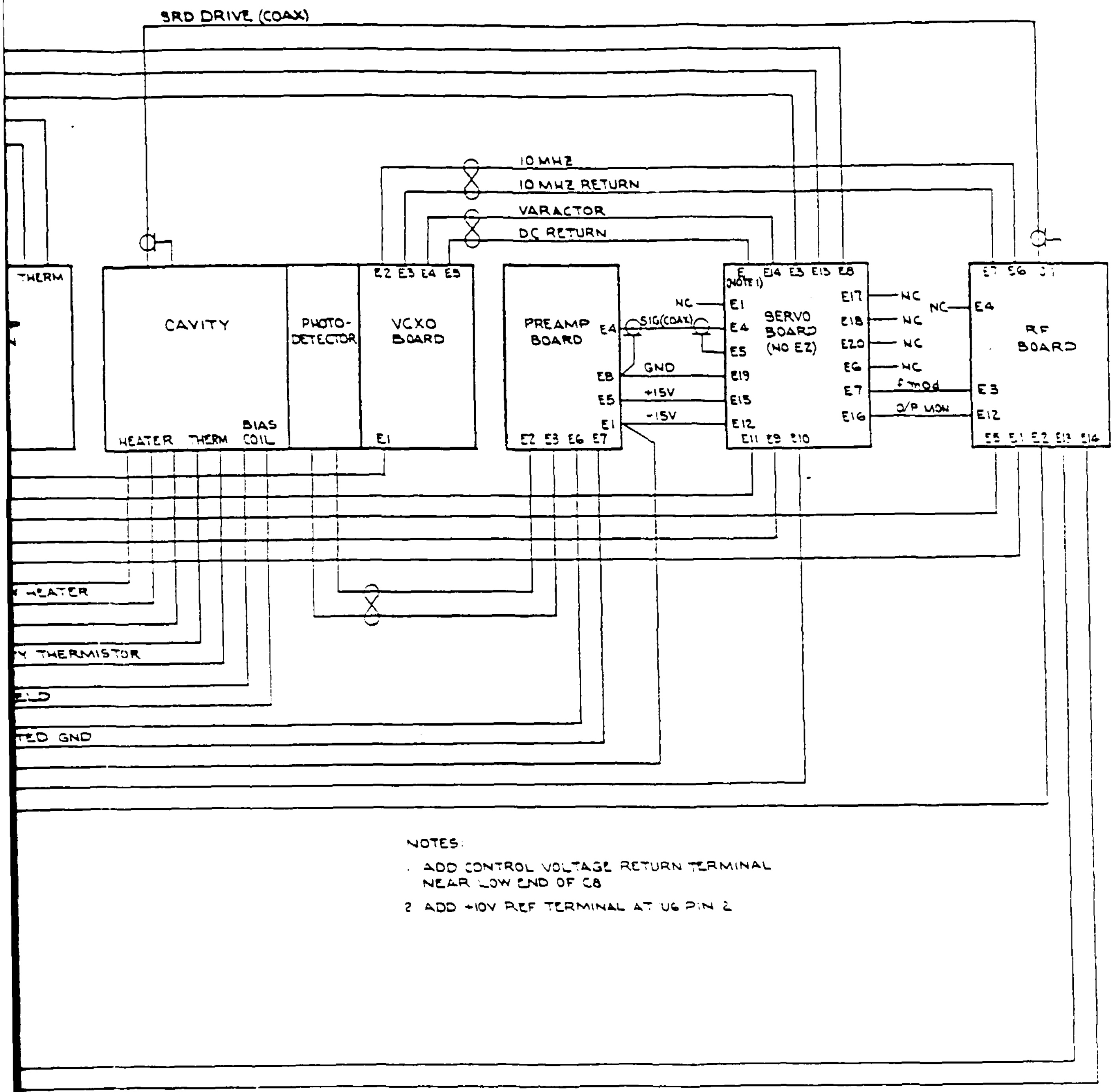



Figure 3.3. TRFS Interconnections.

## 4. DESIGN FEATURES

The EG&G TRFS contains a number of unique design features that combine to give it exceptional performance in a tactical environment. These features are described in the following report sections. In addition, the TRFS has a number of features in common with other EG&G militarized rubidium frequency standards. These standard features are as follows:

1. Ultraminiature physics package with discrete filter cell.

2. High reliability rubidium lamp with calorimetric fill control.

3. Low noise custom photodetector.

4. Current regulated lamp exciter contained within lamp oven assembly.

5. VCXO within physics package assembly.

6. High efficiency switching power circuits.

7. PLL synthesis of direct $f_{Rb}$ submultiple.

8. High frequency squarewave phase modulation.

9. Wide servo bandwidth.

4.1 Thermoelectric Cooling. A particular feature of the EG&G TRFS design is the use of thermoelectric cooling of the physics package to meet the $80^{\circ}C$ maximum baseplate temperature without compromising the stability of the rubidium reference signal. The following discussion provides the rationale for this approach.

To achieve operation at maximum baseplate temperature of $80^{\circ}C$, one would normally require that the physics package and, in particular, the cavity containing both filter and absorption cells, operate no cooler than $90^{\circ}$ - $95^{\circ}C$. This is to allow for a nominal temperature rise from baseplate to cavity and still provide a small regulation range for the cavity oven controller. There is also a tradeoff between cavity to baseplate temperature differential at high baseplate temperature and the power required at low baseplate temperatures.

That cavity temperature is considerably higher than the 75$^{0}$C value at which optimal signal parameters are obtained for the small physics package. The changes necessary to optimize operation at the higher temperatures would result in increased line width due to increased relaxation rates due to spin exchange collisions and would require greater light intensity to maintain signal. The latter will further increase line width and unduly increase the filter cell temperature coefficient. It is estimated that the line width would be increased by 50 from about 800 to 1200 Hz with an attendant reduction in line Q and discriminator slope.

A further disadvantage of higher cell temperatures is the potential for Rb reactions with the $N_2$ component of the buffer gas or Rb loss due to diffusion through the glass. Buffer gas reactions would result in excessive frequency drift. Rb loss would require excessive initial fills leading to vibration problems as excessive Rb "splatters" about the cell in vibration and shock environments.

There are two approaches to circumvent some or all of these problems associated with 80$^{0}$ baseplate temperatures. The first makes use of Raoult's law depression of the rubidium vapor pressure by using a solution of rubidium and potassium. A three-to-one molar ratio of K to Rb would depress the Rb vapor pressure roughly a factor of three. With this approach, the cell running at 90$^{0}$C would have an Rb vapor pressure equivalent to 75$^{0}$C. This would alleviate some of the signal problems, but would leave several high risk unknowns and disadvantages. Among these are uncertainties regarding cell processing, long term stability, vibrational Rb splattering and longer warmup time.

The second approach to alleviating the high baseplate temperature problem is to employ thermoelectric cooling at the upper baseplate temperatures. This is the more favored approach as it eliminates all the unknowns, risks and disadvantages associated with high temperature operation of the physics package. This approach is also consistent with high S/N ratio for good short-term stability and the use of wide servo bandwidth for vibration immunity. The proven cell technology and low operating temperature made feasible by thermoelectric cooling reduce the uncertainties associated with long-term stability of the TRFS. This approach also provides the capability for operation at baseplate temperatures considerably higher than 80°C.

The thermoelectric cooling has been implemented at the physics package (rather than cooling the entire frequency standard) to minimize the amount of heat which must be pumped and the required thermoelectric power. Also, by having the thermoelectrics inside, the overall dimensions of the frequency standard are not affected.

The design also allows internal shock and vibration isolation of the physics package and crystal oscillator, as shown in the cross sectional view of Figure 4.1.1.

A plot of the required thermoelectric power versus baseplate temperature is shown in Figure 4.1.2. Only about 2½ watts is required at 80°C. Experiments with our package indicate that operation to +93°C baseplate temperature is feasible with a thermoelectric cooling power of about 10 watts. The overall power at this very high temperature is, therefore, about the same as it is at the -55°C end. This permits operation to the full MIL-E-5400 class II +95°C intermittent conditions should that ever be required. The thermoelectric cooling also allows the absorption cell to actually operate cooler, thus improving the stability, speeding warmup and reducing operating power.

4.2 Performance Under Vibration. One of the most important challenges associated with the TRFS design was to assure that the unit meets the required performance under exposure to vibration. Besides the usual mechanical packaging constraints, this involves maintaining adequate frequency stability, timing accuracy and spectral purity.

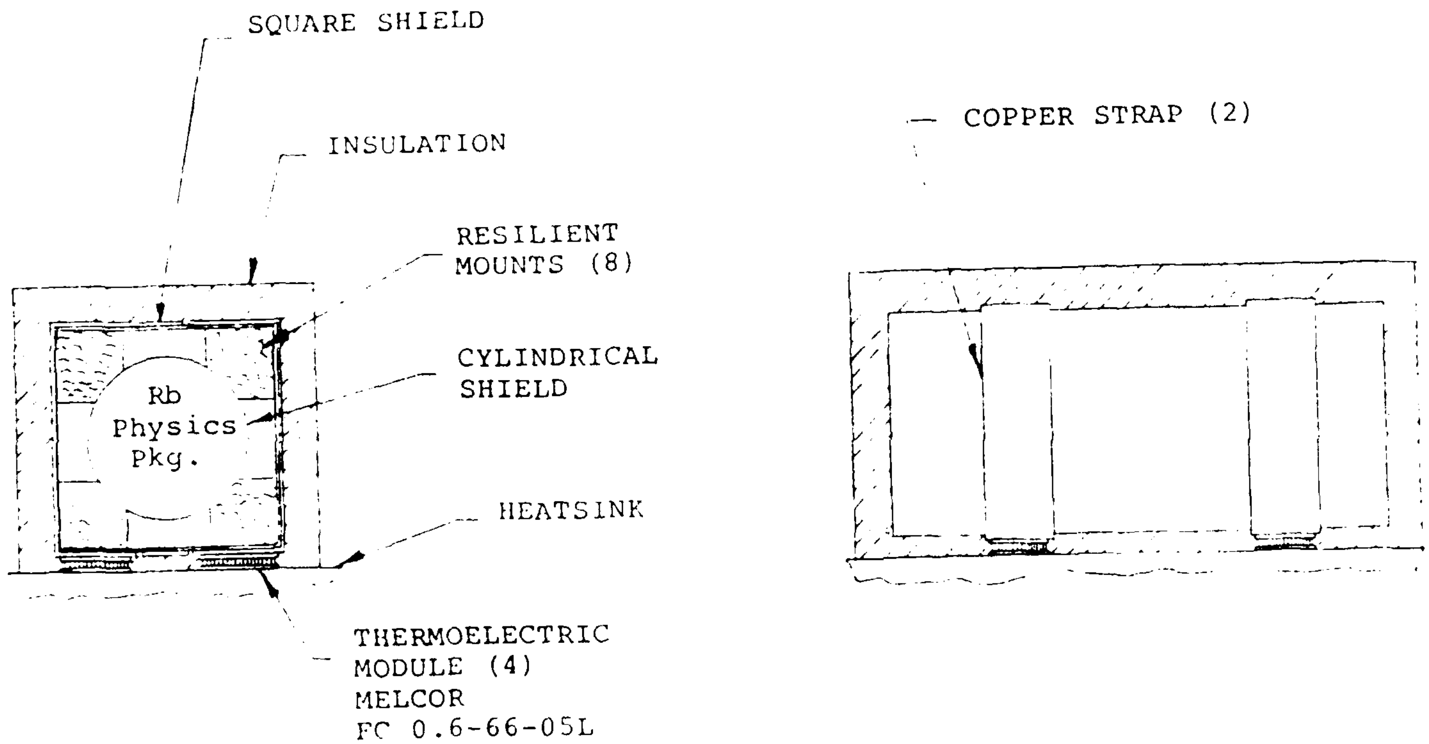



Figure 4.1.1. Thermoelectric Cooling Structure.

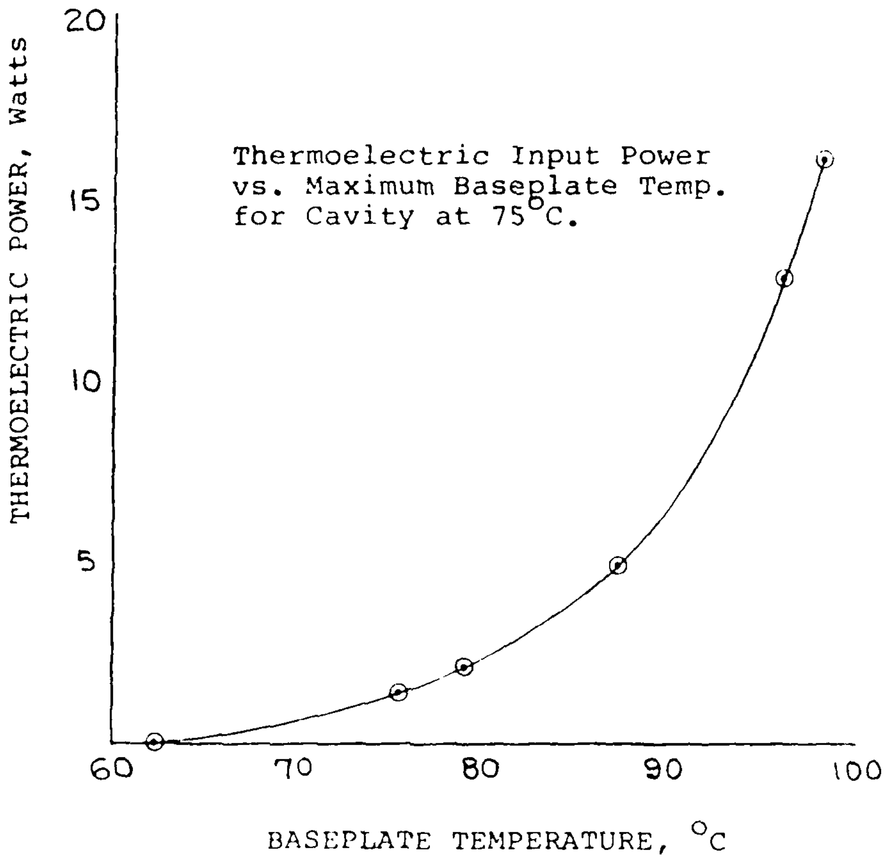



Figure 4.1.2. Thermoelectric Cooling Power.

The TRFS is required to maintain the signal-to-noise performance of paragraph 3.2.1.7 of Appendix A and the -60 dB non-harmonic distortion level of paragraph 3.2.1.8 under the vibration environments of paragraph 3.2.5.3. It is also required to maintain time consistent with a frequency offset of $5 \times 10^{-10}$ under the performance level of random vibration of paragraph 3.2.5.3.1.1 and to have a frequency error of less than $1 \times 10^{-9}$ under the sinusoidal vibration of paragraph 3.2.5.3.2. The EG&G TRFS design meets these requirements by the combination of a vibration-immune Rb physics package, a wide servo bandwidth and a low g sensitivity quartz crystal oscillator.

4.2.1 Basic Considerations. There are two basic ways in which the stability and purity of a rubidium frequency standard are affected by mechanical vibration:

(1) Direct vibrational modulation of the crystal oscillator output.

(2) Indirect disturbance of the crystal oscillator via the servo loop.

The first mechanism, because of correction by the Rb servo, is dominant at vibration frequencies higher than the servo bandwidth, while the second mechanism is dominant at vibration frequencies below the servo bandwidth. Both mechanisms can be important at vibration frequencies near the servo bandwidth.

The second mechanism can be divided into two different causes:

(2a) Spurious recovered signal output from the Rb physics package due to vibrational modulation of the light.

(2b) Spectral purity impairment of the rf excitation to the Rb physics package due to vibrational modulation of the crystal oscillator.

Effect (1) is a broadband dynamic effect that does not produce a frequency offset. Effects (2a) and (b) are usually narrowband effects at the fundamental and 2nd harmonic of the servo modulation rate, $f_{mod}$ and 2 $f_{mod}$, respectively, and can produce a frequency offset. Effect (2b) can also cause offsets over a range of low vibration frequencies.

These effects are summarized in Table 4.2.1.

4.2.2 VCXO Effects. Vibrational modulation of the 10 MHz VCXO is an important factor in the overall performance of the TRFS.

The resonance frequency of a quartz crystal is acceleration dependent. This sensitivity causes the spectral purity, phase jitter, and short-term stability of a crystal oscillator to be degraded by exposure to vibration. Without the atomic reference, this effect extends from static tipover throughout the range of vibration frequencies, and is dependent on crystal cut, construction, orientation, and structural isolation. Spurious components are produced at $\pm f_{vib}$ at a level (dBc) of:

$$L(f_{vib}) = 20 \log_{10} \left[ \frac{\gamma \cdot f_0 \cdot G}{2 \cdot f_{vib}} \right]$$

and frequency stability is degraded to:

$$\sigma_y(\tau) = \gamma \cdot G \cdot \frac{\sin^2(\pi \cdot f_{vib} \cdot \tau)}{\pi \cdot f_{vib} \cdot \tau}$$

where: $\gamma$ = fractional frequency acceleration coefficient ($g^{-1}$)

$G$ = peak acceleration applied to crystal (g)

$\tau$ = averaging time (seconds)

$f_{vib}$ = vibration frequency (Hz)

$f_0$ = carrier frequency (Hz)

TABLE 4.2.1

Vibration Effects Summary

| COMPONENT | EFFECT | $f_{VIB}$ | TYPE | MECHANISM | CURE(s) |
|---|---|---|---|---|---|
| VCXO | Vibrational Modulation of RFS Output (1) | low | FM | Spurious Modulation Sidebands | Wideband servo to correct crystal oscillator |
| | Vibrational Modulation of Microwave Excitation (2b) | low | offset | Loss of carrier power | Wideband servo to correct crystal oscillator |
| | | 2 $f_{mod}$ | offset | Generation of spurious recovered signal | Mechanical isolation, low g-sensitivity, high $f_{mod}$ |
| Rb Physics Package | Vibrational Modulation of Light (2a) | $f_{mod}$ | offset | Generation of spurious recovered signal | Rigid Physics Package construction |

For example, for a crystal having a $\gamma = 1 \times 10^{-9}/g$ along its most sensitive axis and directly exposed to a vibration level of 1 g peak at 5 Hz, the spurious level would be -60 dBc and the resulting frequency stability is shown in Figure 4.2.1.* The average frequency is not affected by this direct modulation of the crystal oscillator.

The situation is improved by the atomic reference to the extent that there is sufficient servo bandwidth to reduce the disturbance, provided that the atomic reference itself is not sensitive to vibration. The EG&G TRFS servo bandwidth is about 100 Hz.

This allows active correction of the crystal oscillator by the rubidium reference at low vibration frequencies that, because of the $f^{-1}$ dependence of phase noise modulation, are the most critical. (This is also the region of vibration frequencies where external and internal vibration isolation is not feasible.)

The main limitation on the maximum possible servo bandwidth is the servo modulation rate, which determines the rate at which information is obtained from the physics package. The modulation rate must be several times higher than the servo bandwidth for reasons of servo stability, phase shift and ripple filtration. The modulation rate is, in turn, subject to a number of trade-offs having to do with the modulation waveform, resonance linewidth, recovered signal amplitude, and phase and frequency offsets introduced by modulation distortion. These tradeoffs have been the subject of extensive investigations at EG&G and have resulted in the choice of squarewave phase modulation. This approach gives optimum recovered signal at high modulation rates as well as relative immunity from modulation distortion effects.

---

* This expression has nulls when $f_{vib} \cdot \tau$ equals an integer since the coherent modulation is averaged out. The envelope falls off as $\tau^{-1}$ and has a maximum value of $3.5 \times 10^{-10}$ at $f_{vib} \cdot \tau \;\; 0.5$

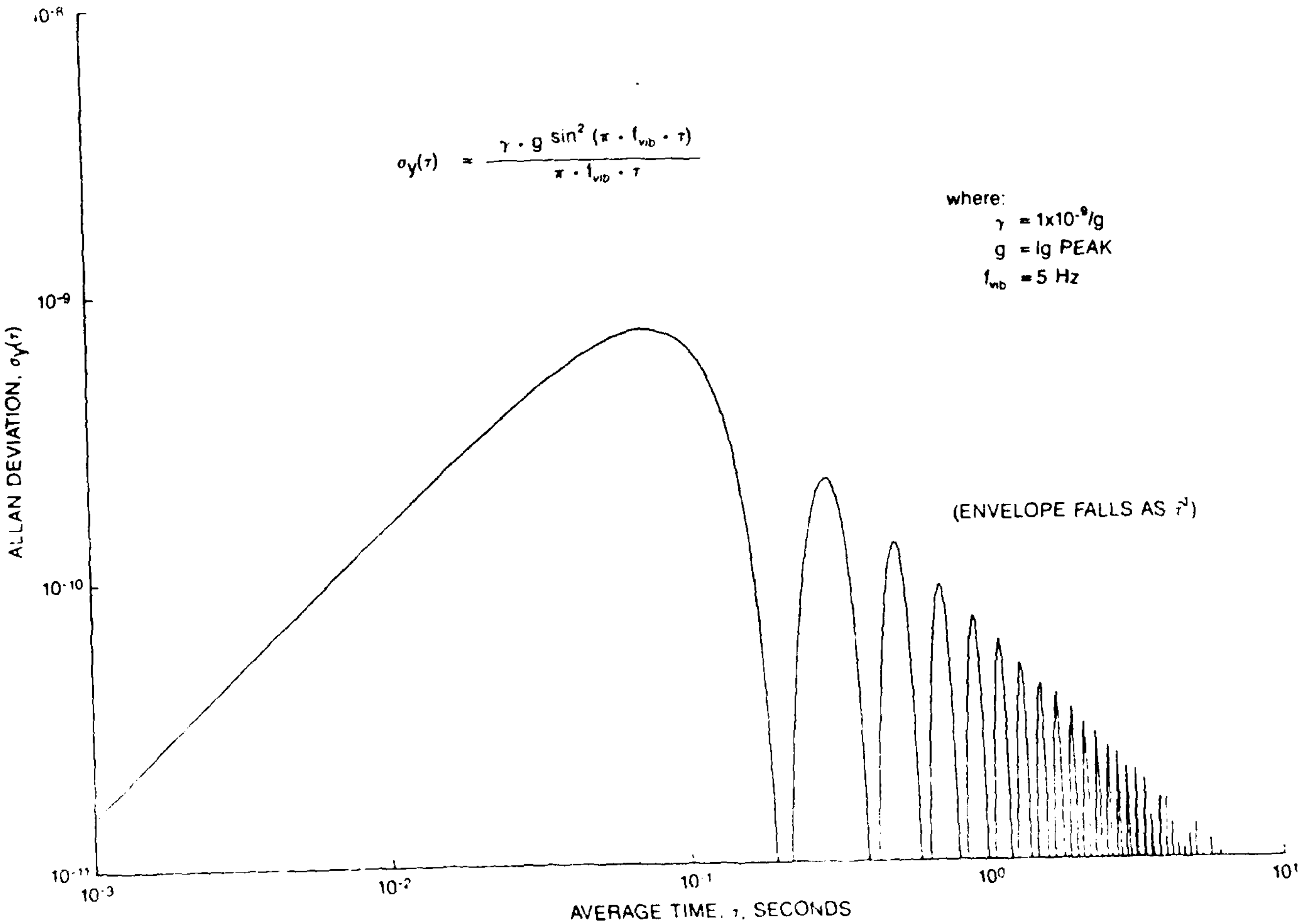



Figure 4.2.1. Allan Variance of Vibrated, Non-corrected Crystal Oscillator.

The wideband servo also avoids spectral purity impairment of the rf excitation to the Rb physics package due to vibrational modulation of the crystal oscillator at low vibration frequencies. Otherwise a considerable portion of the microwave carrier power could be transferred into large amplitude vibrational modulation sidebands. (These sidebands are enhanced by 57 dB by multiplication from 10 MHz to the 6835 MHz rubidium resonance frequency.) It is even possible for the carrier power to become zero at certain modulation indices that result in a Bessel null. The servo correction of the crystal oscillator is able to eliminate this problem.

Another 10 MHz VCXO effect occurs at the 2nd harmonic of the servo modulation rate, where servo correction is not possible. Here vibrational sidebands on the microwave excitation interact with the normal servo modulation to produce a spurious fundamental recovered signal that can cause a frequency offset. This effect is very similar to that of even order modulation distortion and significant frequency offsets are possible. This problem is solved by (1) using a high modulation rate so that its 2nd harmonic is high enough to avoid high g inputs because of external and internal isolation and so that the resulting PM index is lower; and (2) using a low g-sensitivity crystal.

4.2.3 Physics Package Effects. It is necessary that the rubidium physics package be sufficiently free of vibration susceptibility that it can serve as an adequate reference to properly correct the crystal oscillator within the servo bandwidth. If a spurious recovered error signal is produced, the servo, rather than correcting the crystal oscillator vibrational modulation, will impair the stability and purity of the output signal.

A spurious rubidium reference error signal can be produced by mechanical deflection of the physics package light path. This is particularly important at a vibration frequency equal to the servo modulation rate (and perhaps its odd harmonics) since the spurious recovered signal will be processed by the servo amplifier synchronous detector to produce frequency error. A change in light of only about 0.5 ppm under these conditions corresponds to frequency error of $1 \times 10^{-10}$, so extreme rigidity of the physics package light path is required. Motion of the entire physics package is relatively unimportant, but relative motion of the lamp and photodetector, or deflection of any of the optical components (windows, cells or lenses) is very critical. In the EG&G ultra-miniature physics package all these elements are bonded into the lamp and cavity ovens and the ovens are rigidly connected by a stiff cylindrical spacer. (This piece must have relatively low thermal conductivity, however, since the two ovens are at different temperatures. It is therefore a non-metallic material and about the length of the lamp oven.)

Other critical items regarding the physics package vibration sensitivity are the lamp exciter and microwave multiplier. Motion of these items, especially at the servo modulation rate, could also introduce AM on the recovered signal. The EG&G lamp exciter is constructed as part of the lamp oven assembly to avoid motion of the interconnections. Similarly the SRD multiplier is built into the cavity assembly.

The rubidium reference can also be impaired by vibrational modulation of the crystal oscillator causing sidebands on the microwave signal that excites the atomic resonance. These sidebands are symmetrical and cause little frequency offset unless uncorrected by the servo and are at a rate and deviation such that a Bessel null occurs. This latter effect is not a problem with the wide-bandwidth TRFS servo design.

It is also necessary that excessive vibrational modulation not be caused by the synthesizer and rf multiplier chain. In particular, the ~90 MHz crystal oscillator must be tightly locked. (The synthesizer has a PLL bandwidth of about 5 kHz.)

Vibration can also affect the distribution of the rubidium inside the Rb lamp. EG&G has conducted vibration tests specifically to investigate this phenomenon. It is important to avoid excessive Rb fill, yet provide an ample amount to assure satisfactory life. EG&G has conducted extensive research on long-life Rb lamps and uses calorimetry to control lamp fill.

4.2.4 Vibration Isolation. Vibration isolators in the form of silicone rubber pads are included between the magnetic shields of the physics package as shown in Figure 4.1.1. Since the 10 MHz VCXO is part of the cavity assembly inside the physics package, these isolators protect both the VCXO and physics package.

No mechanical isolation is required at low vibration frequencies where there is no physics package vibration sensitivity and where potentially severe modulation of the crystal oscillator is actively corrected by the wideband servo. (This is fortunate because isolation is impractical at low frequencies.) Significant mechanical isolation of the VCXO is desirable, however, at higher vibration frequencies and especially at the critical 2 $f_{mod}$ frequency of about 1600 Hz. Such high frequency vibration isolation is also valuable for shock protection of both the VCXO and physics package.

The most critical design parameter for the vibration isolators is their resonant frequency where actual amplification of the input g level takes place. It is undesirable to locate this where the specified environments also peak since this would further raise the maximum g level at around 33 Hz. It is desirable, however, to locate the isolator resonance low enough so that no significant peaking (and perhaps some useful attenuation) takes place for the critical physics package frequency at $f_{mod}$ (about 800 Hz). Thus the isolator resonance is adjusted for the optimum point at about 200 Hz.

The vibration isolators also have an important thermal function as a primary means of heat transfer from the physics package. Too much conductivity raises the low temperature power requirement and increases the warmup time. Too little conductivity increases the self-heating of the physics package and normally lowers the maximum baseplate operating limit. Fortunately this latter constraint is greatly relaxed by the inclusion of the active thermoelectric cooling and the isolators can be optimized for mechanical and low end power considerations. The temperature rise of the inner cylindrical shield also eliminates extreme changes in the properties of the silicone rubber isolators at low temperatures.

4.2.5 Discrete Spurious. The TRFS discrete spurious requirement (non-harmonic distortion) is -60 dBc and applies at all sideband frequencies. This requirement applies under all environmental conditions and, most particularly, under the operational sinusoidal vibration. Such vibration modulates the crystal oscillator and produces discrete spurious components on the TRFS 10 MHz rf output at a sideband frequency equal to the vibration frequency. The level of these components depends on the g level, frequency and axis of the vibration, the response of the crystal oscillator mounting structure, the g-sensitivity of the crystal (along the particular axis of vibration), and the correction applied by the rubidium servo.

The worst case for the generation of discrete spurious components under vibration occurs in the 30-40 Hz region. Here the applied vibration is the greatest, the frequency is relatively low (which, because of a $f^{-1}$ dependence, increases the spurious level), there is no attenuation from the internal vibration isolators and there is little correction from the servo.

In particular, the largest applied sinusoidal vibration is 14.25 g peak at 32.5 Hz along the vertical axis (due to peaking from the external vibration isolators). Without mount attenuation or servo correction, the maximum allowable crystal g-sensitivity is $4.6 \times 10^{-10}$/g. Some servo correction does occur, however, (about 14 dB or x 5) and the crystal is oriented so that its maximum g-sensitivity is not along this axis. A crystal with a readily achievable g-sensitivity of $1 \times 10^{-9}$/g can therefore meet this requirement.

The situation in the horizontal axis is similar. The maximum g-level is 10.5 g peak at 55 Hz, which, without attenuation or correction requires a crystal g-sensitivity that does not exceed $1.0 \times 10^{-9}$/g. And again, there is some improvement by the servo.

Overall, the discrete spurious under sinusoidal vibration is summarized in Figure 4.2.5.1.

Curve (A) of Figure 4.2.5.1 shows the allowable vibration level (in dB relative to 1 g peak vs vibration frequency in Hz) that can be applied to a crystal having an acceleration sensitivity of $1 \times 10^{-9}$/g and not exceed a discrete spurious level of -60 dBc on the 10 MHz output. This curve applies to the crystal itself in the worst axis without vibration isolation of servo correction. Curves (C), (D), and (E) show the specified levels of sinusoidal vibration for ground mobile and vertical and horizontal axes in airborne applications. The discrete spurious requirement would not be met in the region below about 50 Hz. The EG&G TRFS uses a wide (100 Hz) servo bandwidth as shown in Figure 4.2.5.2 to tightly lock the crystal oscillator to the stable rubidium reference and thus greatly improve this situation. Curve (B) shows the allowable vibration level with the Rb servo. A design margin of about 6 dB (x2) exists.

Furthermore, the crystal sensitivity is less in certain directions and it is aligned so as to further reduce the spurious level for the vertical axis along which the applied vibration is highest.

The EG&G TRFS design therefore meets the spectral purity requirements under the specified levels of sinusoidal vibration.

4.2.6 Phase Noise. The TRFS phase noise (signal to noise) requirements are as follows:

| Sideband Frequency f, Hz | Phase noise SSB, 1 Hz BW L (f), dBc/Hz at 10 MHz |
|---|---|
| 1 | -60 |
| 100 | -80 |
| 1000 | -95 |

These requirements apply under all environmental conditions, including random vibration.

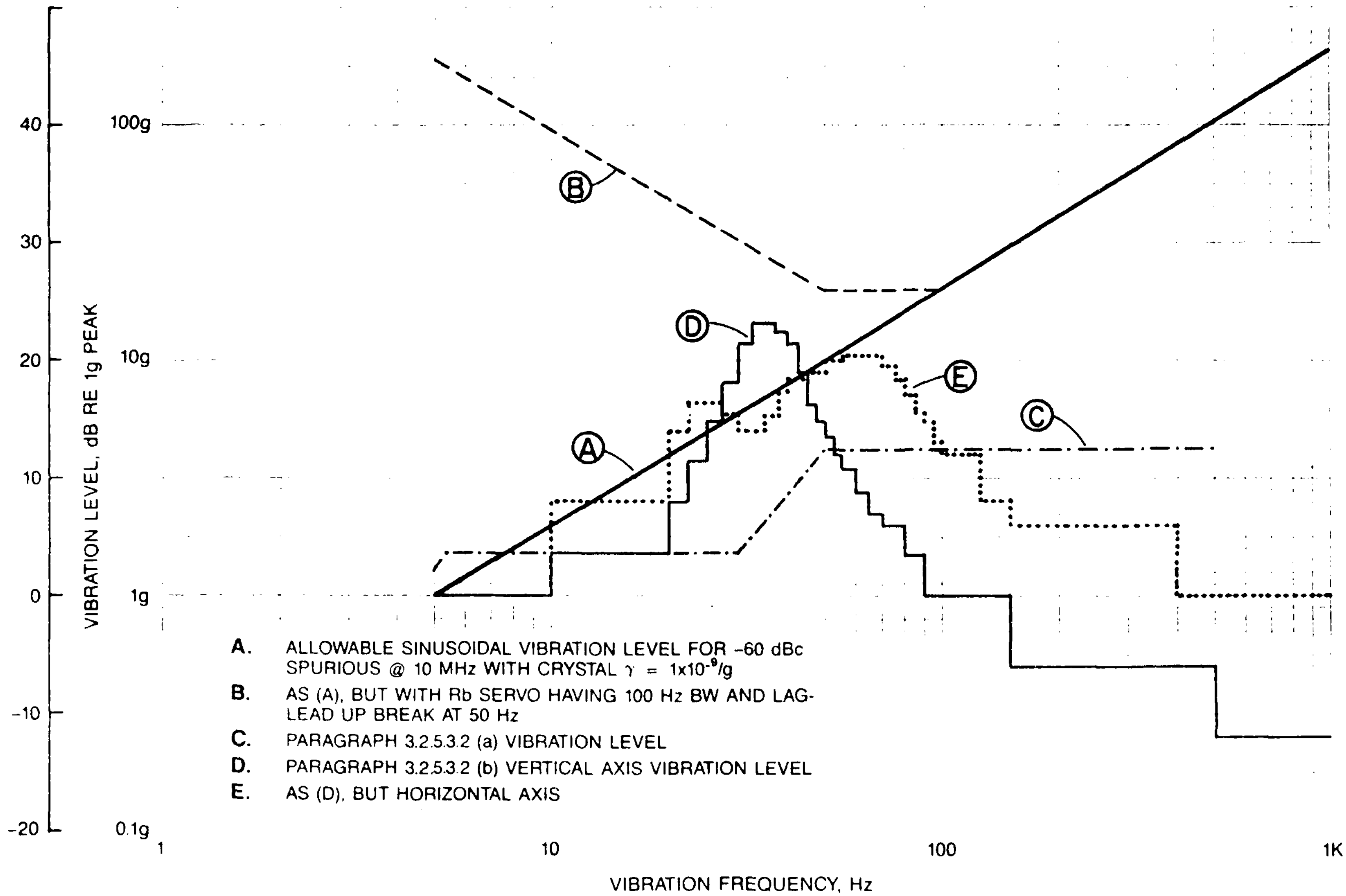



Figure 4.2.5.1. TRFS Sinusoidal Vibration Levels.

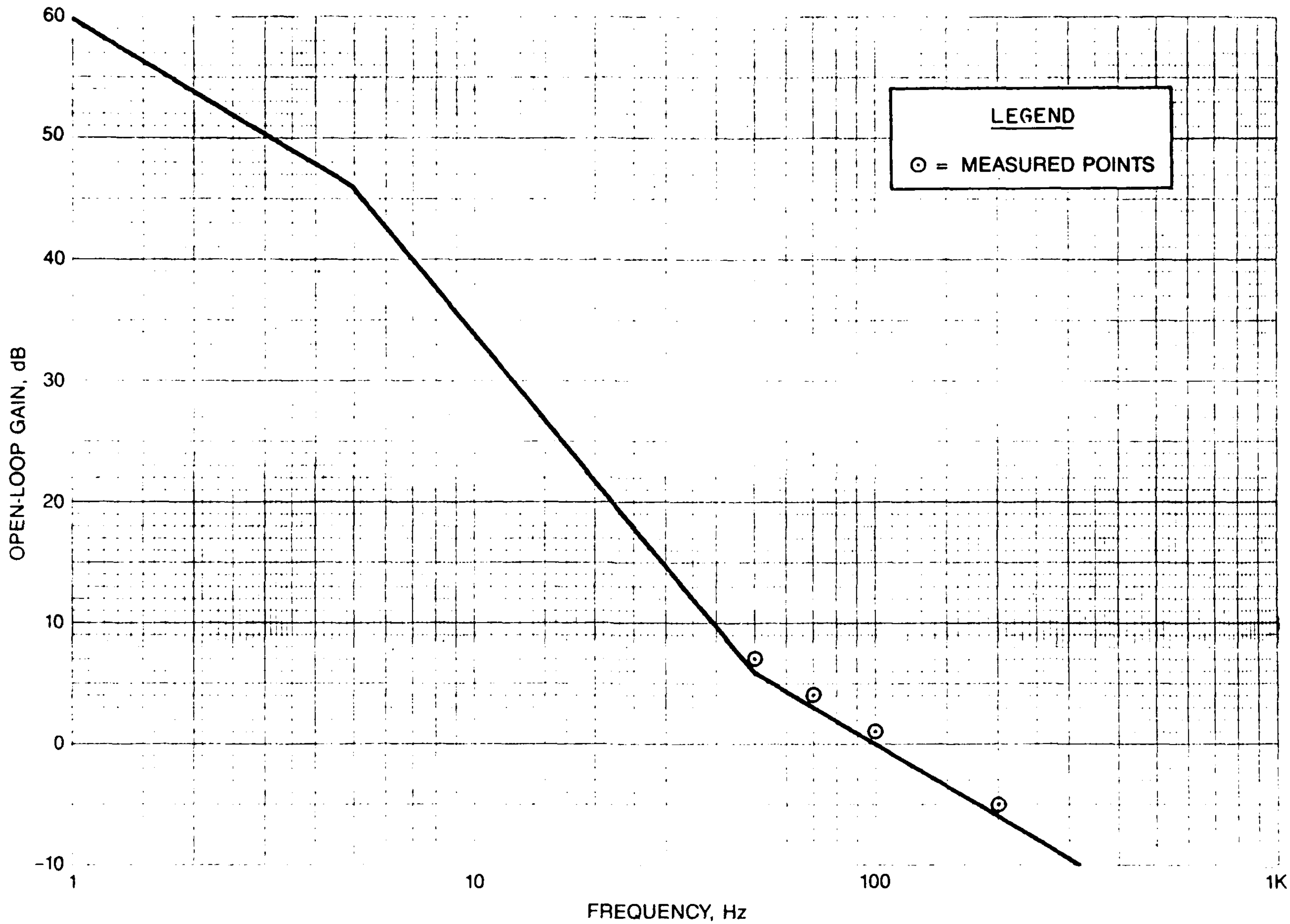



Figure 4.2.5.2. TRFS Servo Gain.

Under quiescent conditions the TRFS phase noise at low sideband frequencies is determined by the noise of the rubidium reference since the crystal oscillator is tightly locked to it by a wide bandwidth servo. The rubidium reference has a white frequency noise characteristic due primarily to shot noise at the photodetector.

This determines the short-term stability of the rubidium reference (and overall TRFS) which is specified as less than $4 \times 10^{-11}\tau^{-1/2}$ for $1 \leq \tau \leq 100$ seconds. When converted to the frequency domain, this corresponds to a phase noise level of L(1) = -68 and L(100) = -108 dBc/Hz at 10 MHz. Somewhat better short-term stability is actually obtained because of the relatively cool cell operating temperature permitted by the thermoelectric cooling and other physics package features. These phase noise requirements are therefore easily met under quiescent conditions.

Under quiescent conditions at low sideband frequencies near the carrier within the 100 Hz Rb servo bandwidth, the L(f) value must be consistent with the S/N ratio of the Rb reference.

At the sideband frequencies above the servo bandwidth (>100 Hz), the TRFS phase noise is determined by its crystal oscillator. A high Q crystal and a low noise oscillator configuration is used and the L(1000) value is about -145 dBc/Hz, greatly exceeding the -95 dBc/Hz requirement under quiescent conditions.

The expected overall TRFS phase noise characteristic under quiescent conditions is shown in Figure 4.2.6.1.

The TRFS phase noise is degraded considerably under exposure to the specified levels of random vibration, but is still able to meet the requirements. This is made possible, primarily, by the wideband servo correction of the low frequency vibrational modulation of the crystal oscillator.

The design levels of TRFS phase noise under random vibration are shown in Figure 4.2.6.2. Below 10 Hz, the phase noise follows the Rb reference

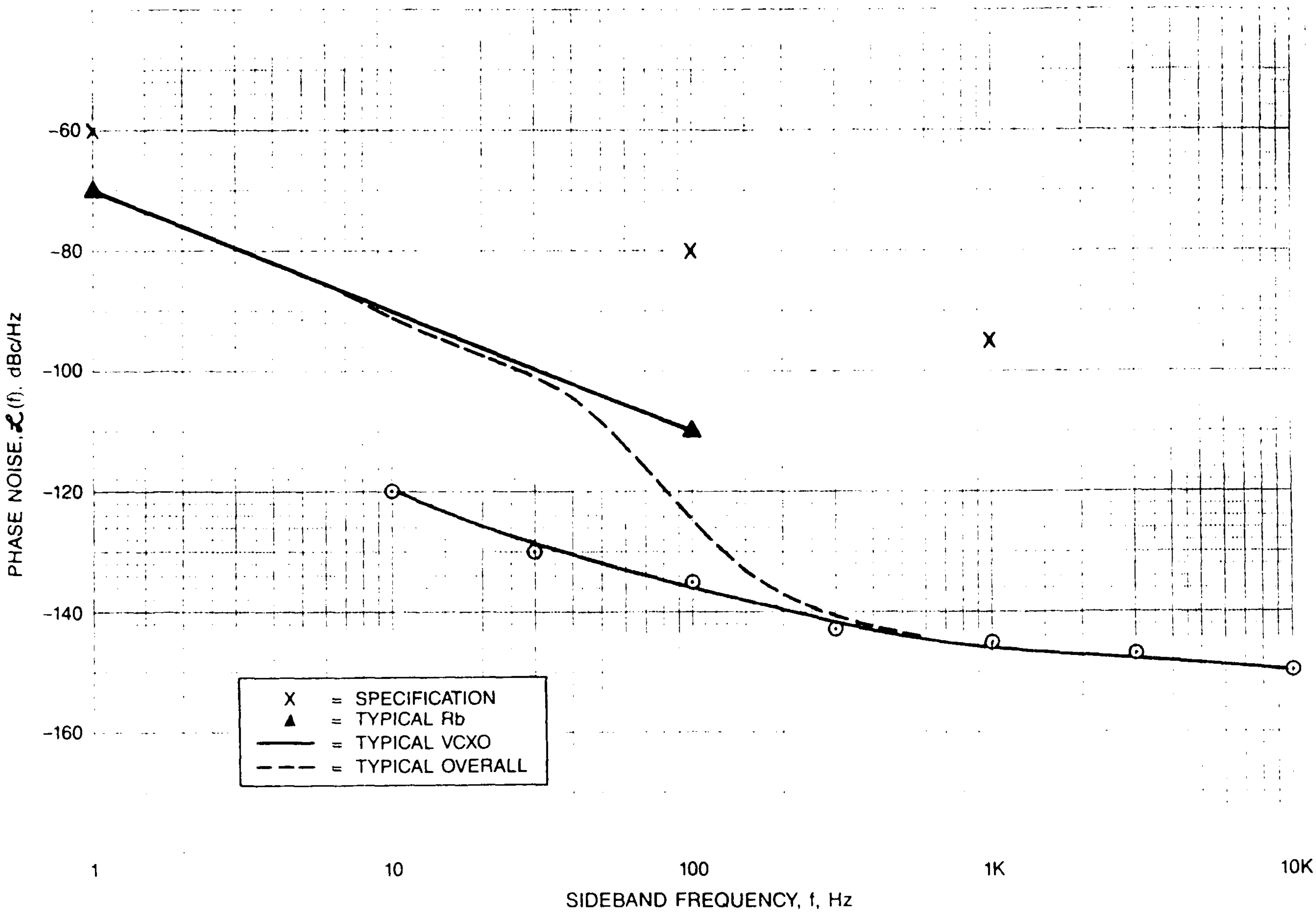



Figure 4.2.6.1. Phase Noise Under Quiescent Conditions.

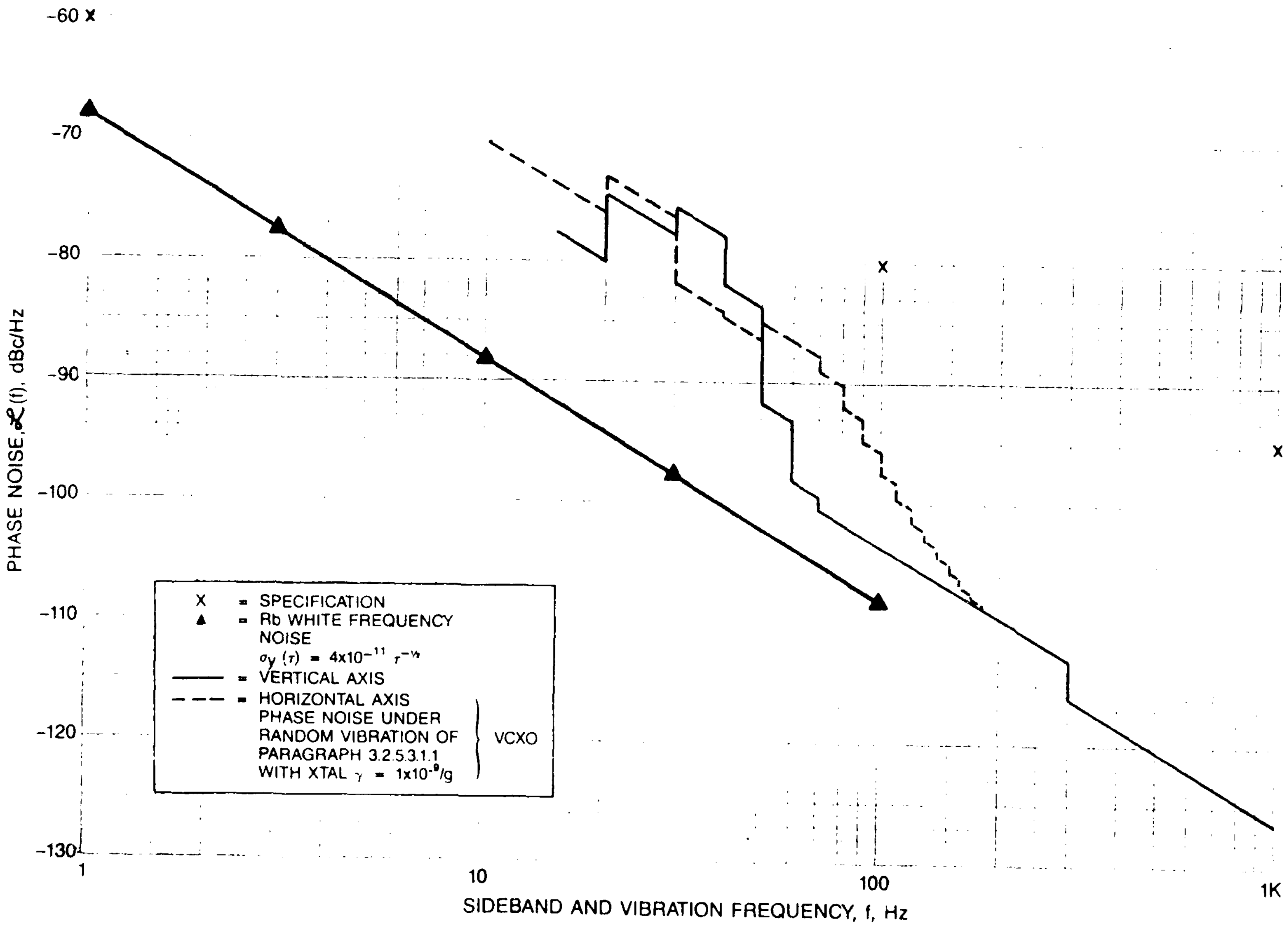



Figure 4.2.6.2. Phase Noise Under Random Vibration.

and above 100 Hz it follows the VCXO. Between 10 and 100 Hz it is somewhat better than for the VCXO alone. In all cases the specified performance is met.

4.2.7 Frequency Stability. Besides the spectral purity requirements (phase noise and discrete spurious), the TRFS must also meet specific frequency stability requirements while exposed to operational vibration. The normal short-term stability specification is replaced by a $1 \times 10^{-9}$ maximum allowable frequency error during exposure to sinusoidal vibration. Averaging times of 1 second below 20 Hz and 0.1 second above 10 Hz are to be used as the vibration frequency is slowly swept.

The most critical aspect of this requirement is that the TRFS not unlock or be subject to unacceptable frequency offsets when the vibration frequency is at or very near the servo modulation rate or its second harmonic.

At other vibration frequencies (not related to the servo modulation rate) no steady state frequency offsets are produced but the frequency scatter can be degraded because of vibrational modulation of the VCXO.

The requirement for a clock error not exceeding 900 nsec during a half-hour exposure to random vibration (corresponding to a frequency offset of less than $5 \times 10^{-10}$) is essentially a requirement that the TRFS remain continuously locked to the Rb reference.

4.3 Power Transient Protection. An important aspect of the TRFS design is the protection of the heater and electronic circuits against power line transients, ripple and reverse polarity.

The TRFS has two input voltage lines with a single ground return. The oven heater power is +28V dc nominal in accordance with MIL-STD-704, Category B (aircraft), MIL-STD-1275 (vehicles) and the specific transient conditions of the TRFS specification. The electronic power is +26V dc nominal in accordance with these same standards except that the ripple and transients are somewhat less severe. Otherwise, the ripple is specified by the CS01 EMI requirements of MIL-STD-461. These power utilization and transient protection requirements are also described in ARINC Report 413. Overall, they have significant design impact and necessitate a number of specific protective measures as described below.

The TRFS power transient protection scheme is shown in the simplified schematic diagram of Figure 4.3. (The individual schematics for the input filter, temperature controller/power supply and thermoelectric controller should also be examined for more specific information. These are Figures 3.7.3, 3.7.1 and 3.7.2 respectively.)

Series diodes are used in the positive leads of both the heater and electronic power input lines. These diodes provide protection for reverse polarity, both transient and sustained. They have PIV ratings that exceed the maximum reverse transient voltages and have average current ratings and heat sinking adequate for the normal TRFS warmup and operation. Their only disadvantage is an efficiency loss of about 4 .

The diodes in each power line are followed by LC filter sections. These filters provide high frequency input ripple attenuation and attenuation of fast transients. They are also necessary to attenuate the conducted emissions from the TRFS power switching circuits (at approximately 50 kHz) in order to meet the CE03 EMI requirements of MIL-STD-461.

The LC filter sections are followed by transient absorbing zener diodes that provide overvoltage protection for the various circuits. The key to the application of these devices is inclusion of sufficient impedance, either the specified transient impedance for the short, high transient voltages, or the TRFS oven heater and thermoelectric impedance or other series resistors.

In addition, the TRFS power input leads have rf filtration directly at the power connector that provides attenuation of high frequency conducted susceptibility and emissions.

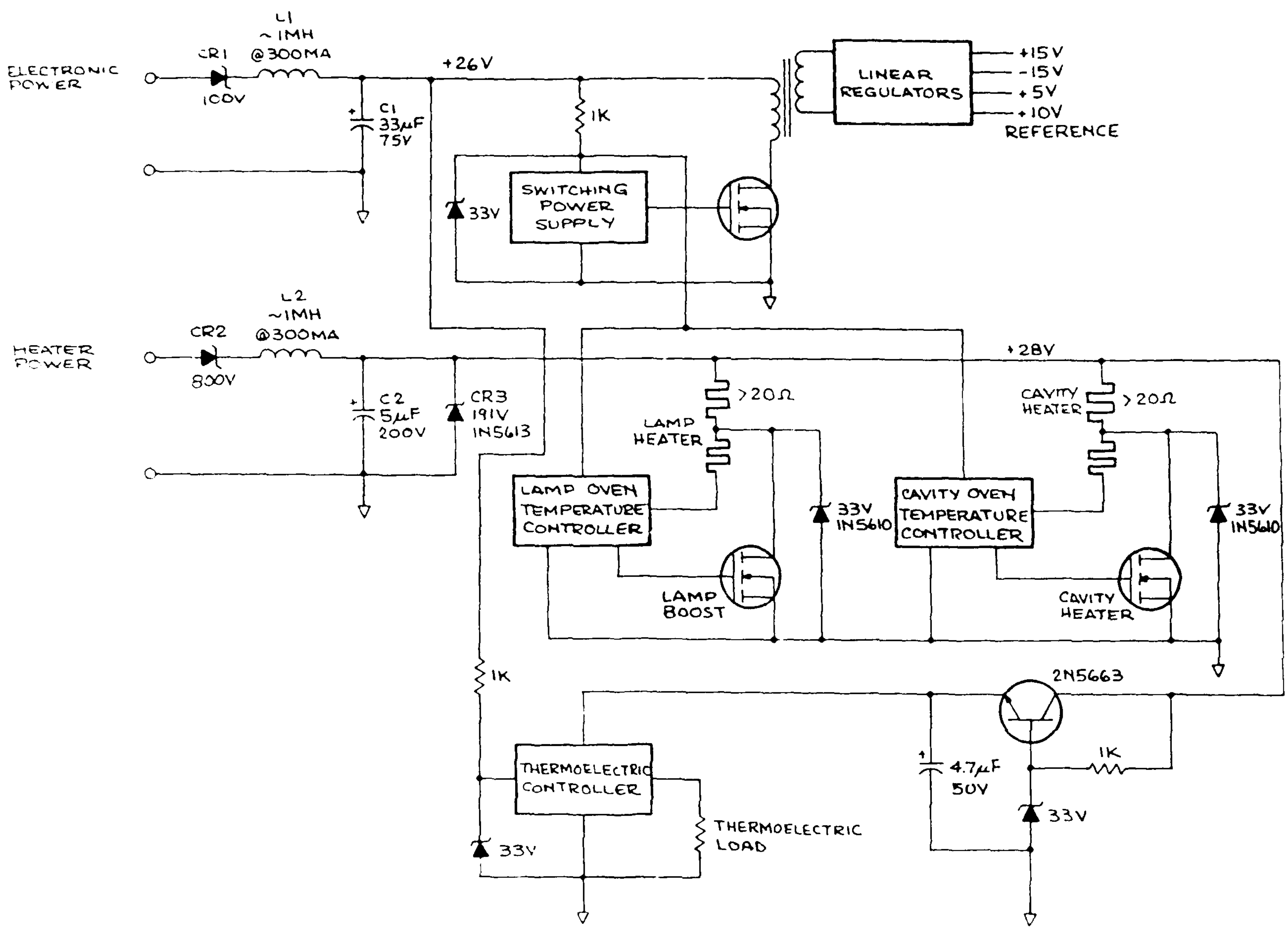



Figure 4.3. Transient Protection Circuits.

4.4 Monitors. The RFS interface diagram (Figure 1 of Appendix A) defines the usage of the 13 J2 pins (see Table 4.4). Two monitor signals are defined: the Resonance Lock (BIT) signal on pin 1 and the Crystal Control Voltage on pin 2.

The Resonance Lock (BIT) output is a go/no-go signal with the electrical characteristics of paragraph 3.2.1.1.b. By combining the Rb servo lock and 10 MHz output level detectors, the BIT detects essentially all ($\geq$ 98.6%) TRFS failures per paragraph 3.2.4.1.1.

The Crystal Control Voltage output is intended to show the need for recalibration of the crystal oscillator to correct for its drift. The EG&G TRFS design uses a high stability precision crystal with a relatively large tuning range and should not require any such recalibration over the 25 year useful lifetime of paragraph 3.2.3.1 and certainly not as often as every 10,000 hours (approximately 1 year) as allowed in paragraph 3.2.4.1.3 (see section 4.5).

TABLE 4.4

J2 Connections

| Pin(s) | Usage |
|---|---|
| 7, 8, 13 | Heater Power |
| 11 | Electronic Power |
| 4, 5, 12 | Ground |
| 1 | BIT (Lock) |
| 2 | Control Voltage Monitor |
| 6 | Spare |
| 3 | Not Used |
| 10 | Not Used |
| 9 | Spare |

4.5 VCXO Trimming. The varactor tuning range of the 10 MHz VCXO is wide enough that no mechanical trimmer is required for coarse frequency adjustments. Not only does this eliminate the necessity for any form of preventative maintenance (and the attendant logistics effort and cost) but it also eliminates a relatively large, unreliable and vibration sensitive component.

4.6 Warmup and Power Consumption. The EG&G TRFS contains provisions for ultra-fast warmup. The TRFS must lock up in only 1.5 minutes and achieve a frequency tolerance of $5 \times 10^{-10}$ within 2.5 minutes at room temperature (and within 4.0 minutes at $-55^{o}C$). This is accomplished with low additional complexity by adding a tap to the foil oven heaters and using one section alone as a boost heater during warmup, thereby increasing the oven demand power. This is accomplished with only 1 additional wire for each oven and a simple controller switch circuit. The total TRFS demand power is only about 95 W. at maximum supply voltages, less than the 110 W. allowed.

EG&G has conducted thermal fatigue testing on the TRFS ultrafast warmup physics package design and has proven its ability to withstand thousands of on-off cycles.

The EG&G TRFS also has low power consumption under steady state conditions. The TRFS power consumption is summarized in Table 4.6.

TABLE 4.6

TRFS Power Consumption (Watts)

| Condition | Spec | Actual |
|---|---|---|
| Warmup | 110 | 74 * |
| $-55^{o}C$ | 23 | 18 |
| $+25^{o}C$ | 17 | 12 |
| $+80^{o}C$ | -- | 10 |

* At nominal supply voltages

## 5. RELIABILITY

A detailed parts stress reliability analysis per MIL-STD-217D was conducted on the TRFS design under the specified conditions. This analysis is included as Appendix B to this report and the results are summarized in Table 5.0 below. The predicted reliability is well within that required in paragraph 3.2.3 of the specifications.

TABLE 5.0

TRFS MTBF Prediction Summary

| Environment | Cooling Air Temperature | MTBF Specified | (Hours) Predicted |
|---|---|---|---|
| Airborne Uninhabited, Fighter (AUF) | $2^{o}C$ | 12,975 | 23,683 |
| Ground Fixed (GF) | $30^{o}C$ | 34,408 | 101,802 |
| Ground Mobile (GM) | $40^{o}C$ | 21,352 | 36,224 |

# 6. ENGINEERING TESTS

Engineering tests were conducted as appropriate throughout the TRFS development effort in accordance with paragraph 4.1.2.3 of the specifications and good engineering practice.

Some of the more significant of these engineering tests that involve items not otherwise covered by the qualification tests are discussed in the following report sections.

6.1 Warm-up Endurance. The warm-up of a rubidium frequency standard subjects the physics package to thermal fatigue stress, particularly when a relatively high demand power is used to achieve fast warm-up. Engineering tests were therefore conducted to verify the ability of the TRFS design to endure thousands of turn-on cycles.

A physics package with warm-up boost heaters was assembled and instrumented early in the TRFS development program and has accumulated over 7500 turn-on cycles over a period of 25 months without any sign of wearout. Our confidence in the design is further strengthened by similar testing conducted on complete EG&G RbXO units where four RbXOs were on-off cycled twenty times per day while being subjected to a -62 to +68$^{0}$C temperature cycle for 180 days. These units withstood over 14,000 on-off cycles, 700 temperature cycles and 18,000 operating hours under these severe conditions with a single failure. Furthermore, the one failure mechanism, lack of stress relief in a bead thermistor lead, was corrected.

6.2 Crystal g-Sensitivity. 2-g tipover tests were conducted on four TRFS crystal oscillators. These tests measured the static g-sensitivity of the four 10 MHz 3rd overtone SC-cut TO-8 crystals while operating in TRFS oscillator boards in a special test oven.

The test results are shown in Table 6.2. The crystal g-sensitivities are at or below 1 x $10^{-9}$/g along the principal axes and the resultant vector sensitivities are at or slightly above 1 x $10^{-9}$/g. This is adequate to meet the TRFS requirements as discussed in section 4.2 of this report.

Crystal g-sensitivity, $\gamma$, $pp10^9/g$

| S/N | AXIS | | | | | | Resultant (Static) |
|---|---|---|---|---|---|---|---|
| | X | | Y | | Z | | |
| | Static | Dynamic | Static | Dynamic | Static | Dynamic | |
| 1 | 1.0 | 1.1 | 0.1 | 0.4 | 0.4 | 0.6 | 1.1 |
| 4 | 1.1 | 1.1 | 0.3 | 0.3 | 0.6 | 0.3 | 1.3 |
| 7 | 0.9 | - | 0.4 | - | 0.2 | - | 1.0 |
| 8 | 0.8 | 1.3 | 0.4 | 0.2 | 0.5 | 0.8 | 1.0 |

Crystal g-Sensitivity Measurements

Table 6.2

Dynamic vibration tests were also conducted on three of these oscillators. Their rf spectrum was observed while undergoing 5 g peak sinusoidal vibration at 100 Hz and the resulting sideband levels were related to the crystal g-sensitivity. These results (also shown in Table 6.2) are in good agreement with the static measurements. These dynamic tests were also conducted with random vibration and at vibration frequencies between 25 and 2000 Hz at levels up to 10 g, with similar results.

6.3 Vibration Resistance. To verify that the TRFS package was capable of withstanding the specified vibration levels, the two major assemblies were subjected to the worst of the vibration levels. The first was the assembly of the physics package, magnetic shields, resilient mounts, and thermoelectric modules. Measurements of the response of various elements were made using a hand held vibration probe, and modes observed with a strobe. The resistances of the thermoelectric modules were measured before and after vibration to check for fracture of the thermoelectric elements or solder joints.

The other assembly tested included the main structure with printed circuit boards mounted. The outer cover was left off to allow measurements with a hand held vibration probe and observation with a strobe, but it was structurally simulated by a sheet metal back support. Although no failures occurred, the testing indicated improvements in the mounting of the printed circuit boards which were incorporated into the design.

# 7. QUALIFICATION TESTS

Qualification tests were conducted on two TRFS Full Scale Engineering Models in accordance with a TRFS Qualification Test Plan prepared for the U.S. Air Force Electronic Systems Division by Support Systems Associates, Inc. (see Appendix C). With only minor exceptions as noted in the detailed test reports, the EG&G TRFS design is fully compliant with the requirements as evidenced by passage of all qualification tests. The detailed test reports that follow are organized according to the qualification test sequence given on the test plan. A summary of the qualification test compliance is shown in Table 7.0.

7.1 Physical Inspection. The two TRFS full scale engineering models were inspected for compliance with the physical requirements of weight, dimensions,finish and connectors per paragraph 5.0 of the test plan. Both units were fully compliant with the requirements.

7.2 Performance Tests. Performance tests covering the main TRFS performance parameters were conducted on both full scale engineering models in accordance with Section 6 of the test plan. The results of these tests are shown on the Performance Test Data Sheets, Table 7.2. A more detailed description of each of these tests is given in the following report sections.

7.2.1 Harmonic/Nonharmonic Distortion. The levels of harmonic and nonharmonic (spurious) distortion on the TRFS 10 MHz output are limited to -30 dBc and -60 dBc respectively per paragraph 3.2.1.8 of the specifications. These distortion components were measured on both full scale engineering models using a rf spectrum analyzer as shown in Figure 6-1 of the test plan. A crystal notch filter was used to lower the level of the 10 MHz carrier to improve the dynamic range of the spurious measurement. The results of these tests are shown in Table 7.2; both units comply with the requirements.

Compliance with the -60 dBc spurious level is also required under conditions of sinusoidal vibration and was one of the most important design considerations for the TRFS. This requirement is also met, as described in Section 7.4.4 of this report.

TABLE 7.0

Qualification Test Compliance Summary

| Test Plan Para.# | Test | S/N 101 | S/N 102 | Remarks |
|---|---|---|---|---|
| 5.0 | Physical Inspection | ✓ | ✓ | |
| 6.1 | Harmonics/Non-Harmonics | ✓ | ✓ | |
| 6.2 | Voltage Sensitivity | ✓ | ✓ | |
| 6.3 | Frequency Adjustability | ✓ | ✓ | |
| 6.4 | Orientation Sensitivity | ✓ | ✓ | |
| 6.5 | Magnetic Sensitivity | * | ✓ | shields unannealed |
| 6.6 | Frequency Retrace | ✓ | ✓ | |
| 6.7 | Built-In Test | ✓ | ✓ | |
| 6.8 | Crystal Control Voltage | ✓ | ✓ | |
| 6.9 | Short Circuit Protection | ✓ | ✓ | |
| 6.10 | Short-Term Stability | ✓ | ✓ | |
| 6.11 . | Output Impedance | ✓ | ✓ | |
| 6.12 | *Warm-Up & Power Consumption* | ✓ | ✓ | |
| 6.13 | Signal-to-Noise | ✓ | ✓ | |
| 7.1 | Output & Frequency | ✓ | ✓ | |
| 8.1 | Temperature/Altitude | ✓ | ✓ | |
| 8.2 | Temperature Shock | ✓ | ✓ | |
| 8.3 | Random Vibration | - | ✓ | |
| 8.4 | Sinusoidal Vibration | - | ✓ | |
| 8.5 | Bench Handling | - | ✓ | |
| 8.6 | Operational Shock | - | ✓ | |
| 8.7 | Acceleration | - | ✓ | |
| 8.8 | Acoustic Noise | - | ✓ | |
| 8.9 | Humidity | ✓ | - | |
| 8.10 | Fungus | ✓ | ✓ | |
| 8.11 | Explosive Atmosphere | ✓ | - | |
| 8.12 | Rain | - | ✓ | |
| 8.13 | Salt Fog | ✓ | - | |
| 8.14 | Sand & Dust | ✓ | - | |
| 9.0 | EMI | * ✓ | - | 2 minor outages |
| 10.1 | Long Term Stability | ✓ | ✓ | |

Legend: ✓ = passed
- = tested
* = see remarks

Table 7.2

TRFS PERFORMANCE TEST DATA SHEET | S/N 101

SEQUENCE *Final* | DATE: 11/5 - 12/15/86

INITIALS: KDL, WJR

| PARAMETER | VALUE | LIMITS | UNITS | ✓ |
|---|---|---|---|---|
| **Output:** | | | | |
| Level | 0.55 | 0.45-0.65 | Vrms | (✓) |
| Harmonic (max.) | -40 | ≤-30 | dBc | (✓) |
| Spurious (max.) ≥70KHz | -60 | ≤-60 | dBc | (✓) |
| **Voltage Sensitivity:** | | | | |
| 23.4-28.6(Elect.) | <.5 | ≤ 1 | $pp10^{11}$ * | (✓) |
| 22.0-32.0(Elect.) | 1.0 | ≤ 5 | $pp10^{11}$ * | (✓) |
| Heater Dropout | -.003 | ≤ 1 | $pp10^{8}$ | (✓) |
| **Adjustment Range:** | | | | |
| Maximum | 1.6 | | $pp10^{9}$ | |
| Minimum | -3.4 | | $pp10^{9}$ | |
| Range | 5 | ≥3 | $pp10^{9}$ | (✓) |
| Setting | ±1.5 | ±2 | $pp10^{11}$ | (✓) |
| **Orientation Sensitivity:** | | | | |
| Normal' | -2 | | $pp10^{11}$ | |
| Left Side Down | <1 | 5 | $pp10^{11}$ * | (✓) |
| Top Side Down | <1 | 5 | $pp10^{11}$ * | (✓) |
| Right Side Down | <1 | 5 | $pp10^{11}$ * | (✓) |
| Back Side Down | +1 | 5 | $pp10^{11}$ * | (✓) |
| Front Side Down | -1 | 5 | $pp10^{11}$ * | (✓) |
| **Magnetic Sensitivity:** | | | | |
| X-Axis | 6 | ≤2 | $pp10^{11}$/Gauss | (NG) |
| Y-Axis | 0.5 | ≤2 | $pp10^{11}$/Gauss | (✓) |
| Z-Axis | 0.2 | ≤2 | $pp10^{11}$/Gauss | (✓) |
| **Retrace:** | | | | |
| Initial | -2.3 | | $pp10^{11}$ | |
| Turnon #1 | -1.0 | | $pp10^{11}$ | |
| Turnon #2 | -2.1 | | $pp10^{11}$ | |
| Turnon #3 | -1.2 | | $pp10^{11}$ | |
| Error (max.) | 1.3 | ≤5 | $pp10^{11}$ * | (✓) |
| **BIT:** | | | | |
| Leakage | <10 | <100 | μAdc | (✓) |
| Voltage | .08 | ≤1 | Vdc | (✓) |
| **Control Voltage:** | | | | |
| Voltage | 8.54 | 5.5-9.5 | Vdc | (✓) |

TRFS PERFORMANCE TEST DATA SHEET (cont'd)

| PARAMETER | VALUE | LIMITS | UNITS | ✓ |
|---|---|---|---|---|
| **Short-Circuit Protection:** | | | | |
| Initial Output | .55 | 0.45-0.65 | Vrms | ( ✓ ) |
| Initial Frequency | +0.7 | ±5 | $pp10^{11}$ | ( ✓ ) |
| Final Output | .55 | 0.45-0.65 | Vrms | ( ✓ ) |
| Frequency Change | -1.0 | ≤5 | $pp10^{11}$ * | ( ✓ ) |
| **Short-Term Stability:** | | | | |
| 1 Second | 2.00 | ≤4 | $pp10^{11}$ | ( ✓ ) |
| 10 Seconds | .695 | ≤1.265 | $pp10^{11}$ | ( ✓ ) |
| 100 Seconds | 1.78 | ≤4 | $pp10^{12}$ | ( ✓ ) |
| **Output Impedance:** | | | | |
| Impedance | 52.37 | 45-55 ~~40-60~~ | Ohms | ( ✓ ) |
| **Warmup and Power:** | | | | |
| Peak Current (28V) | 1.8 | | Adc | |
| Peak Current (26V) | .280 | | Adc | |
| Input Voltage(28V) | 28.0 | | Vdc | |
| Input Voltage(26V) | 26.0 | | Vdc | |
| Input Power(Total) | 57.7 | ≤110 | Wdc | ( ✓ ) |
| Lock Time | 78 | ≤90 | Sec | ( ✓ ) |
| 2.0 Minute Accuracy | 1.0 | ≤1 | $pp10^{9}$ | ( ✓ ) |
| 2.5 Minute Accuracy | 4.4 | ≤5 | $pp10^{10}$ | ( ✓ ) |
| Steady-State Power(Total) | 9.5 | ≤17 | Wdc | ( ✓ ) |
| **Signal to Noise:** | | | | |
| 1 Hz | -73 | ≤-60 | dBc/Hz | ( ✓ ) |
| 100 Hz | -135 | ≤-80 | dBc/Hz | ( ✓ ) |
| 1000 Hz | -139 | ≤-95 | dBc/Hz | ( ✓ ) |

Remarks:

*Relative Δf/f

TRFS PERFORMANCE TEST DATA SHEET

SEQUENCE Final

S/N 102

DATE: 12/15 - 12/19/86

INITIALS: KDL, WJR

| PARAMETER | VALUE | LIMITS | UNITS | ✓ |
|---|---|---|---|---|
| **Output:** | | | | |
| Level | .57 | 0.45-0.65 | Vrms | (✓) |
| Harmonic (max.) | -42 | ≤-30 | dBc | (✓) |
| Spurious (max.) | 89MHz -60 | ≤-60 | dBc | (✓) |
| **Voltage Sensitivity:** | | | | |
| 23.4-28.6(Elect.) | .5 | ≤ 1 | $pp10^{11}$ * | (✓) |
| 22.0-32.0(Elect.) | 1.0 | ≤ 5 | $pp10^{11}$ * | (✓) |
| Heater Dropout | <.002 | ≤ 1 | $pp10^{8}$ | (✓) |
| **Adjustment Range:** | | | | |
| Maximum | +3.4 | | $pp10^{9}$ | |
| Minimum | -2.4 | | $pp10^{9}$ | |
| Range | 5.8 | ≥3 | $pp10^{9}$ | (✓) |
| Setting | ±0 | ±2 | $pp10^{11}$ | (✓) |
| **Orientation Sensitivity:** | | | | |
| Normal | +59 | | $pp10^{11}$ | |
| Left Side Down | +2 | 5 | $pp10^{11}$ * | (✓) |
| Top Side Down | +3 | 5 | $pp10^{11}$ * | (✓) |
| Right Side Down | +3 | 5 | $pp10^{11}$ * | (✓) |
| Back Side Down | +1 | 5 | $pp10^{11}$ * | (✓) |
| Front Side Down | 0 | 5 | $pp10^{11}$ * | (✓) |
| **Magnetic Sensitivity:** | | | | |
| X-Axis | .83 | ≤2 | $pp10^{11}$/Gauss | (✓) |
| Y-Axis | <.1 | ≤2 | $pp10^{11}$/Gauss | (✓) |
| Z-Axis | <.1 | ≤2 | $pp10^{11}$/Gauss | (✓) |
| **Retrace:** | | | | |
| Initial | -0.6 | | $pp10^{11}$ | |
| Turnon #1 | -2.0 | | $pp10^{11}$ | |
| Turnon #2 | -1.5 | | $pp10^{11}$ | |
| Turnon #3 | +4.0 | | $pp10^{11}$ | |
| Error (max.) | +4.6 | ≤5 | $pp10^{11}$ * | (✓) |
| **BIT:** | | | | |
| Leakage | <10 | <100 | µAdc | (✓) |
| Voltage | .113 | ≤1 | Vdc | (✓) |
| **Control Voltage:** | | | | |
| Voltage | 7.96 | 5.5-9.5 | Vdc | (✓) |

TRFS PERFORMANCE TEST DATA SHEET (cont'd)

| PARAMETER | VALUE | LIMITS | UNITS | ✓ |
|---|---|---|---|---|
| Short-Circuit Protection: | | | | |
| Initial Output | .57 | 0.45-0.65 | Vrms | ( ✓ ) |
| Initial Frequency | +3 | ±5 | pp$10^{11}$ | ( ✓ ) |
| Final Output | .57 | 0.45-0.65 | Vrms | ( ✓ ) |
| Frequency Change | + 2 | ≤5 | pp$10^{11}$ * | ( ✓ ) |
| Short-Term Stability: | | | | |
| 1 Second | 2.6 | ≤4 | pp$10^{11}$ | ( ✓ ) |
| 10 Seconds | 0.79 | ≤1.265 | pp$10^{11}$ | ( ✓ ) |
| 100 Seconds | 2.9 | ≤4 | pp$10^{12}$ | ( ✓ ) |
| Output Impedance: | | | | |
| Impedance | 45.92 | 45-55 ~~40-60~~ | Ohms | ( ✓ ) |
| Warmup and Power: | | | | |
| Peak Current (28V) | 2.3 | | Adc | |
| Peak Current (26V) | .364 | | Adc | |
| Input Voltage(28V) | 28 | | Vdc | |
| Input Voltage(26V) | 26 | | Vdc | |
| Input Power(Total) | 74 | ≤110 | Wdc | ( ✓ ) |
| Lock Time | 70.5 | ≤90 | Sec | ( ✓ ) |
| 2.0 Minute Accuracy | .71 | ≤1 | pp$10^{9}$ | ( ✓ ) |
| 2.5 Minute Accuracy | 3.4 | ≤5 | pp$10^{10}$ | ( ✓ ) |
| Steady-State Power(Total) | 11.86 | ≤17 | Wdc | ( ✓ ) |
| Signal to Noise: | | | | |
| 1 Hz | -71 | ≤-60 | dBc/Hz | ( ✓ ) |
| 100 Hz | -137 | ≤-80 | dBc/Hz | ( ✓ ) |
| 1000 Hz | -140 | ≤-95 | dBc/Hz | ( ✓ ) |

Remarks:

*Relative Δf/f

7.2.2 Voltage Sensitivity. The voltage sensitivity of the TRFS output frequency is limited to less than $1 \times 10^{-11}$ for a 10% input voltage change and to less than $5 \times 10^{-11}$ over the entire voltage range. The frequency must also change less than $1 \times 10^{-8}$ during a 10 second drop-out of the heater voltage. These requirements are given in paragraph 3.2.1.6 of the specifications.

The voltage sensitivity of both TRFS full-scale engineering models was measured by varying the electronic and heater supply voltages per the table of paragraph 6.2 (B) of the test plan while using the high resolution frequency measuring system of Appendix E. The results of these tests are shown in Table 7.2; both units comply with the requirements.

7.2.3 Frequency Adjustability. The TRFS is required to have a frequency adjustment range of $3 \times 10^{-9}$ settable within $2 \times 10^{-11}$ per paragraph 3.2.1.3 of the specifications.

Measurements were made of the frequency adjustability of both full scale engineering models using the high resolution frequency measuring system of Appendix E. The results of these are shown in Table 7.2; both units comply with the requirements.

7.2.4 Orientation Sensitivity. The TRFS must meet all performance requirements regardless of orientation per paragraph 3.2.2.5 of the specifications and the orientation sensitivity is limited to $5 \times 10^{-11}$ per paragraph 6.4 of the test plan.

Measurements were made of the orientation sensitivity of both full scale engineering models using the high resolution frequency measuring system of Appendix E. The results of these tests are shown in Table 7.2; both units comply with the requirements.

7.2.5 Magnetic Sensitivity. The TRFS magnetic sensitivity is limited to $2 \times 10^{-11}$/gauss per paragraph 3.2.1.9 of the specifications.

Measurements were made of the magnetic sensitivity by placing the TRFS inside a Helmholtz coil pair and using the high resolution frequency measuring system of Appendix E to measure the frequency change due to the reversal of a 4 gauss field along each major axis. The Helmholtz coils were 4 feet in diameter and constructed per ASTM Specification 346-64, Standard Method of Test of Magnetic Shielding. The field was calibrated using a gaussmeter probe at their center without the TRFS and the coil was located at least 10 feet away from large metallic objects.

The results of the magnetic sensitivity measurements are shown in Table 7.2. The TRFS is most sensitive along the X-axis, the magnetic axis of the physics package. The magnetic shields of TRFS S/N 101 were not annealed and did not have their design values of permeability and shielding factor. TRFS S/N 102 (and all subsequent units) have annealed shields and easily comply with the requirements.

7.2.6 Frequency Retrace. The TRFS frequency retrace for multiple on-off cycling at constant temperature is required to be better than $5 \times 10^{-11}$ and to be non-cumulative.

Measurements were made of the frequency retrace of both full scale engineering models using the high resolution frequency measuring system of Appendix E. The results of these tests are shown in Table 7.2; both units comply with the requirements.

EG&G has also conducted extensive on-off stability tests on its similar RbXO unit. Four RbXOs showed a long-term retrace characteristic that was under $\pm 5 \times 10^{-13}$/day after 6 months and 3600 on-off cycles, essentially identical to their performance when operating continuously.

7.2.7 Built-In Test. The TRFS design includes a built-in test (BIT) output per paragraph 3.2.1.1. (B) of the specifications.

The characteristics of this BIT signal were checked on both full scale engineering models by measuring with a digital multimeter, the leakage current and voltage drop at this output in the "no-go" and "go" states, respectively per paragraph 6.7 of the test plan. The results are shown in Table 7.2; both units comply with the requirements.

7.2.8 <u>Crystal Control Voltage</u>. The TRFS design includes a crystal control voltage analog monitor that indicates the margin remaining for lock of the crystal oscillator to the Rb reference. This voltage must be +7.5 V ± 2V at shipment and remain betwen +3 and +12 V per paragraph 3.2.1.1 (C) of the specifications.

The crystal control voltage was measured on both full scale engineering models using a digital multimeter per paragraph 6.8 of the test plan. The results are shown in Table 7.2; both units comply with the requirements.

7.2.9 <u>Short-Circuit Protection</u>. All TRFS outputs are required to be short-circuit proof per paragraph 3.2.1.15 of the specifications.

Checks were made on both full scale engineering models per paragraph 6.9 of the test plan that confirmed that there was no performance degradation after any J1 or J2 output was shorted to ground.

7.2.10 <u>Short-Term Stability</u>. The TRFS is required to have a short-term stability of at least $4 \times 10^{-11}\ \tau^{-1/2}$ for averaging times, $\tau$, between 1 and 100 seconds per paragraph 3.2.1.4.2 of the specifications.

Measurements were made on both full scale engineering models using the high resolution frequency measuring system of Appendix E to verify compliance with the short-term stability requirement per paragraph 6.10 of the test plan. These data are shown in Table 7.2; both units comply with the requirements.

7.2.11 <u>Output Impedance</u>. The output impedance of the TRFS 10 MHz output is required to be 50 ohms ± 10 per paragraph 3.2.1.1 (A) of the specifications.

The output impedance was determined for each of the two full scale engineering models by measuring the change in output voltage as the load resistance was varied. The results are shown in Table 7.2; both units comply with the requirements.

7.2.12 Warm-up and Power Consumption. The TRFS warm-up and power consumption requirements are defined in paragraphs 3.2.12 and 3.2.11 respectively of the specifications.

Tests were made regarding the warm-up and power consumption characteristics of both full scale engineering models in accordance with paragraph 6.12 of the test plan. The test setup included the high resolution frequency measuring system of Appendix E and instruments to measure and record the TRFS power consumption. The results are listed in Table 7.2. TRFS S/N 102, which has the final design values of heater resistances and demand power, fully complies with the warm-up requirements. Both units comply with the power consumption requirements.

7.2.13 Signal-To-Noise. The TRFS signal-to-noise (phase noise) requirements are given in paragraph 3.2.1.7 of the specifications.

Measurements of the phase noise characteristics of both full scale engineering models were made in accordance with paragraph 6.13 of the test plan. The test setup included a 10 MHz low noise reference crystal oscillator (Piezo Model 2810007), a double-balanced mixer, low-pass filter and low noise amplifier, and a audio frequency wave analyzer. The reference oscillator was phase-locked to the TRFS via a slow ($\tau > 1$ sec) loop filter and the mixer output was adjusted for 0 Vdc so that it would function as a phase demodulator. Such a setup is a standard means for measuring phase noise.

The results of these phase noise measurements are shown in Table 7.2. Both units easily comply with the requirements.

## 7.3 Functional Tests

Functional tests were conducted on both TRFS full scale engineering models in accordance with paragraph 7.0 of the Qualification Test Plan before and after exposure to each of the environmental tests described in the next section of this report. The purpose of these functional tests was to verify that the unit was operating properly. The parameters measured by the functional test were TRFS output level and frequency, dc input power and VCXO control voltage.

An example of a typical functional test data sheet is shown in Table 7.3. All functional tests were successfully passed.

## 7.4 Environmental Tests

A series of environmental tests were conducted on the TRFS full scale engineering models to verify that the design complies fully with all performance requirements under the environmental conditons specified in paragraph 3.2.5 of the TRFS specifications.

The general procedure followed was to perform a functional test on the unit under test before and after each of the environmental tests. Most of the tests followed a MIL-STD-810 test method, with the specific test conditions in accordance with the TRFS Qualification Test Plan and specifications. In most cases the relevant TRFS performance parameters were observed during the tests.

TRFS FUNCTIONAL TEST DATA SHEET

SEQUENCE ____________

S/N ____________

DATE: ____________

INITIALS: ____________

| PARAMETER | VALUE | LIMITS | UNITS | ✓ |
|---|---|---|---|---|
| Output level | ____ | 0.45-0.65 | Vrms | ( ) |
| Output Frequency | ____ | $\pm 5$ | $pp10^{11}$ | ( ) |
| Power: | | | | |
| Voltage (Elect.) | ____ | 26 (nom.) | Vdc | |
| Current (Elect.) | ____ | | Adc | |
| Voltage (Htr) | ____ | 28 (nom.) | Vdc | |
| Current (Htr) | ____ | | Adc | |
| Power (Total) | ____ | $\leq 17$ | Wdc | ( ) |
| Control Voltage | ____ | 3-12 | Vdc | ( ) |

Remarks:

Table 7.3

### 7.4.1 Temperature/Altitude

The temperature/altitude test was performed on TRFS S/Ns 101 & 102 in accordance with paragraph 8.1 of the Qualification Test Plan. This test involved the temperature and pressure sensitivity of the unit per paragraphs 3.2.1.13 and 3.2.1.14 respectively of the TRFS specifications under the temperature and altitude environmental conditions of paragraph 3.2.5.1. The temperature/altitude test was that of MIL-STD-810C, Method 504.1, Procedure I. All requirements were met. Details of the test are as follows:

Test Item: TRFS S/N 101 and S/N 102

Spec: QTP 8.1
MIL-STD-810C, Method 504.1, Procedure I.

Test Completion Date: 12/17/86

Test Setup: See Figure 7.4.1

Test Facility: EG&G, Salem, MA

Procedure/Results:

Note: Each step represents a separate test condition applied independently of the others, per MIL-STD-810C.

1. With the test unit (S/N 102) deenergized, the chamber temperature was adjusted to -62$^{0}$C and the unit allowed to stabilize. This condition was maintained for 2 hours.

2. With the test unit (S/N 102) deenergized, the chamber temperature was adjusted to -54$^{0}$C and the unit allowed to stabilize. The unit was then energized at 22 Vdc. The unit achieved a frequency offset of $5 \times 10^{-10}$ in less than four minutes. The peak input power of 51 watts met the specification (<11[illegible] watts). The steady power of 19 watts met specification (<23 watts). Frequency offset after one hour met specification (<5 x $10^{-10}$).

The unit was deenergized and restabilized at -54$^{\circ}$C. The operational sequence was repeated two additional times. Frequency readings at 1 hour for the last two cycles deviated less than $5 \times 10^{-11}$.

3. The test unit (S/N 101) was stabilized at -54$^{\circ}$C and 32 Vdc. The chamber pressure was reduced from 1 atmosphere to 70,000 ft. The observed barometric coefficient was $5 \times 10^{-14}$/mbar which meets the specification of $<1 \times 10^{-13}$/mbar.

4. The test unit (S/N 101), deenergized, was stabilized at -10$^{\circ}$C. The chamber door was opened and frost allowed to form on the unit (It was necessary to spray water around the unit). When the frost melted, the door was closed. The unit was energized at 32 Vdc for five minutes; A Functional Test was performed and passed and then the unit was deenergized for five minutes, a total of three times.

5. The test unit (S/N 102), deenergized, was stabilized at 95$^{\circ}$C and soaked for 16 hours. After exposure, a Functional Test was performed and passed.

6. The test unit was mounted on a heatsink, and the five exposed surfaces of the unit were covered with blanket insulation to allow air flow over the heatsink only. The chamber temperature was increased to 71$^{\circ}$C, and the unit stabilized at 32 Vdc. The chamber temperature was adjusted slightly to bring the unit baseplate temperature to 71$^{\circ}$C plus 0.45$^{\circ}$C per watt of power consumption, or 76$^{\circ}$C for unit power consumption of 10.8 watts. After four hours of operation, the frequency offset was less than $3 \times 10^{-10}$.

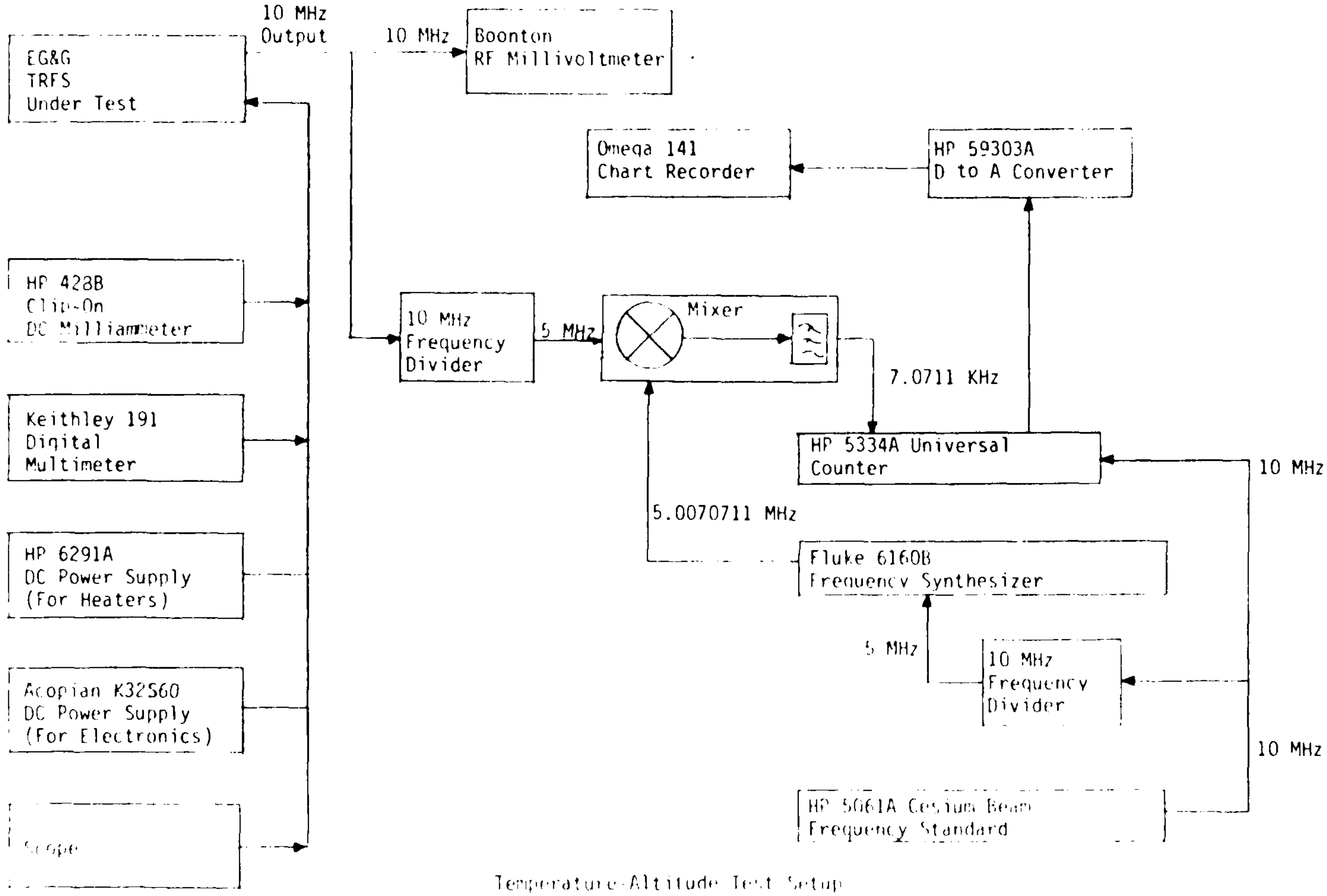
7. The test unit (S/N 102) was stabilized at 36$^{\circ}$C and 32 Vdc. The chamber pressure was reduced from 1 atmosphere to 50,000 ft. and maintained for 4 hours. The observed barometric coefficient

was 5 x $10^{-14}$/mbar, which meets the specification of <1 x $10^{-13}$/mbar.

8. The test unit (S/N 102) was stabilized at 60°C and 32 Vdc. The chamber pressure was reduced from 1 atmosphere to 50,000 ft. The unit was energized for 30 minutes then deenergized for 50 minutes, a total of four times. The highest observed barometric coefficient (including retrace) was 6 x $10^{-14}$/mbar, which meets the specification of 1 x $10^{-13}$/mbar.

9. The test unit (S/N 102) was stabilized at 10°C and 32 Vdc. The chamber pressure was reduced from 1 atmosphere to 70,000 ft. and maintained for 4 hours. The observed barometric coefficient was 4 x $10^{-14}$/mbar, which meets the specification of <1 x $10^{-13}$/mbar.

10. The test unit (S/N 102) was stabilized at 35°C and 32 Vdc. The chamber pressure was reduced from 1 atmosphere to 70,000 ft. The unit was energized for 30 minutes then deenergized for 15 minutes, a total of four times. The highest observed barometric coefficient (including retrace) was 6 x $10^{-14}$/mbar which meets the specification of <1 x $10^{-13}$/mbar.




Temperature-Altitude Test Setup

Figure 7.4.1

### 7.4.2 Temperature Shock

A temperature shock test was performed on TRFS S/N 102 in accordance with paragraph 8.2 of the Qualification Test Plan. This test involved the temperature sensitivity of the unit per paragraph 3.2.1.13 of the TRFS specifications under the temperature transient and shock environmental conditions of paragraphs 3.2.5.1.3 and 3.2.5.1.4 respectively. The temperature shock test was that of MIL-STD-810, Method 503.1, Procedure I. All requirements were met. Details of the test are as follows:

Test Item: TRFS S/N 102 (Steps A-G) and S/N 101 (Steps I-O)

Spec: QTP 8.2
MIL-STD-810C, Method 503.1, Procedure I

Test Dates: 10/31/86 - 11/2/86 (Steps A-G), 12/3/86 (Steps I-O)

Test Facility: EG&G, Salem, MA

Procedure/Results - Nonoperating, Steps A-G:

1. The test unit, nonoperating, was placed in a temperature chamber (Tenney Mite 3). The chamber temperature was raised to 71°C and maintained for 4 hours.

2. The unit was transferred within 5 minutes to a cold chamber (Tenney Jr.) at -57°C and maintained for 4 hours.

3. The unit was transferred within 5 minutes to the hot chamber and maintained for 4 hours.

4. These steps were repeated for a total of 3 full cycles (approximately 24 hours total).

5. The unit was inspected for damage and none observed. A Functional Test was performed and passed.

Procedure/Results - Operating, Steps 1-0:

1. The test unit was mounted on a heat sink and set up per Figure 7.4.2.1.

2. The chamber temperature was increased to 71°C and the unit allowed to stabilize. The unit was turned on and operated for 1 hour.

3. With the unit operating, the chamber temperature was cycled between 71°C and -55°C at a rate of between 2 and 3°C per minute with a 30 minute soak at each temperature limit. Three full cycles were performed (approximately 10 hrs total test time). The frequency variation was within specification (3 pp $10^{10}$), as shown by attached frequency record, Figure 7.4.2.2.

Temperature Shock Test Setup

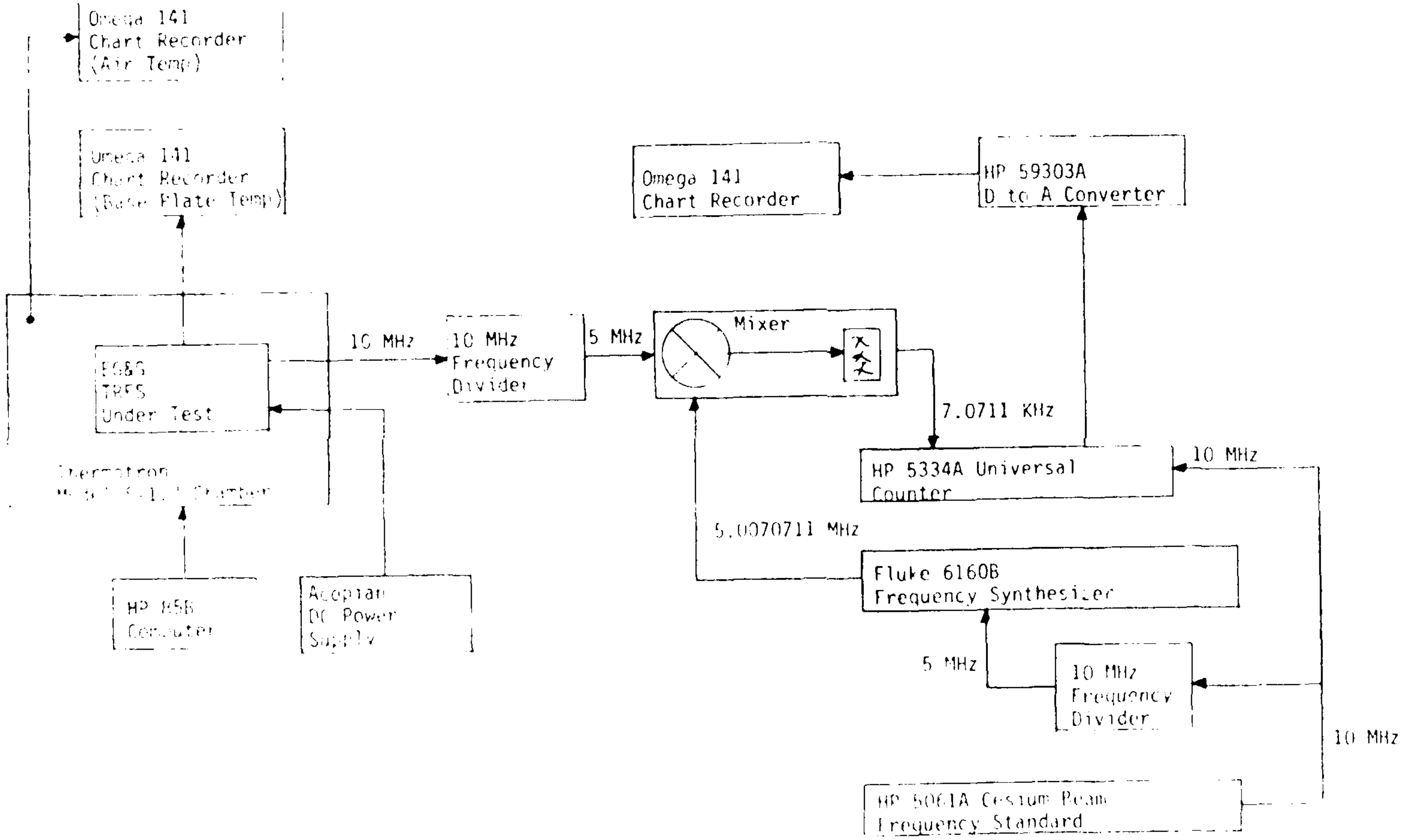
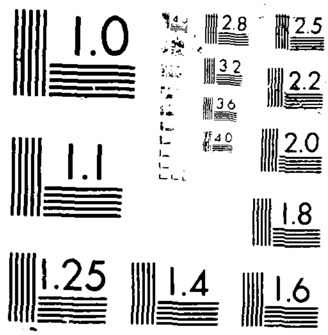
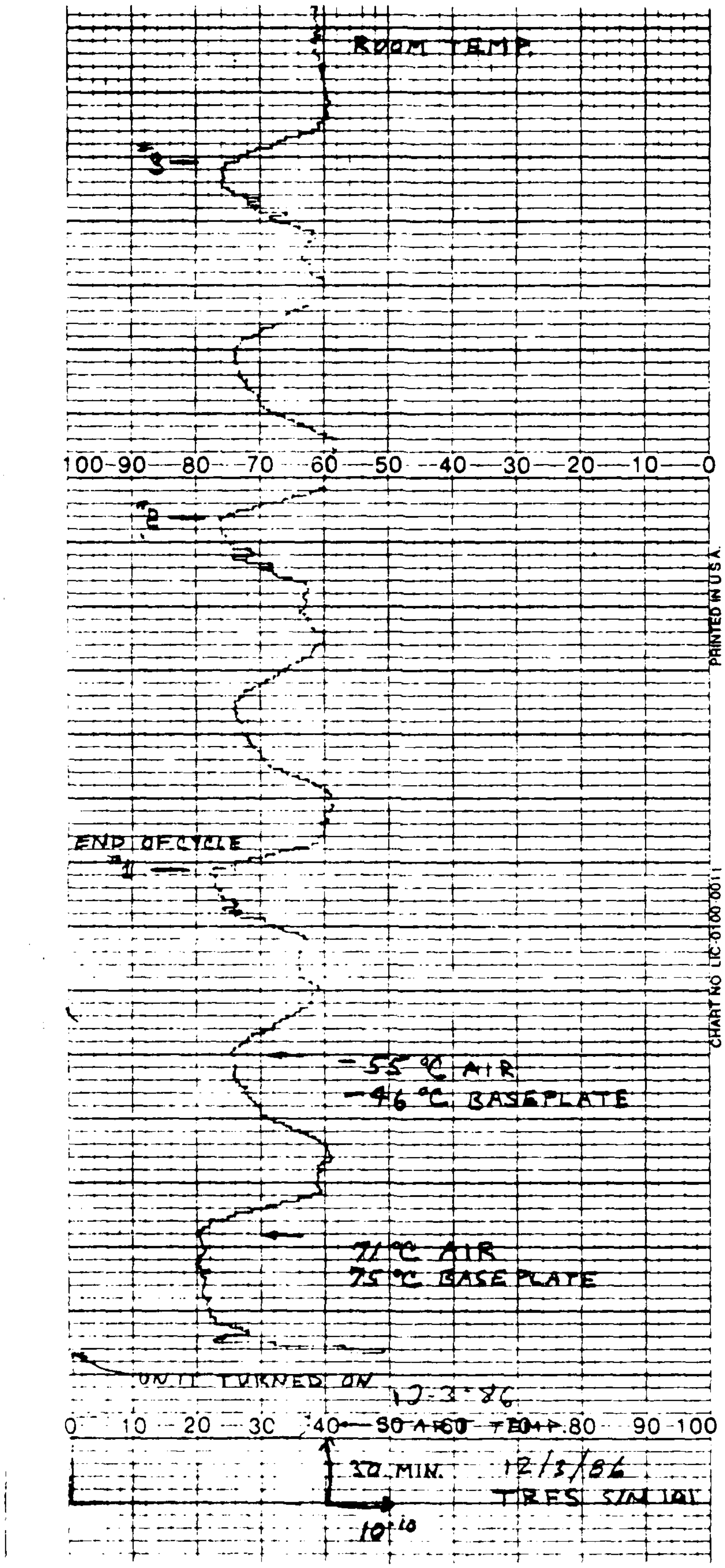



Figure 7.4.2.1

AD-A192 901 TACTICAL RUBIDIUM FREQUENCY STANDARD (TRFS) VOLUME 1 2/2
(U) EG AND G INC SALEM MA FREQUENCY PRODUCTS DIV
T J LYNCH ET AL. OCT 87 RADC-TR-87-166-VOL-1

UNCLASSIFIED F19628-83-C-0175 F/G 14/2 NL


1.0
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6




Frequency Record, Temp Shock Test
Figure 7.4.2.2

### 7.4.3 Random Vibration

Random vibration tests were performed on TRFS S/N 102 in accordance with paragraph 8.3 of the Qualification Test Plan. These tests involved the phase noise and frequency stability of the unit per paragraphs 3.2.1.7 and 3.2.5.3.1.1 respectively of the TRFS specifications under the performance levels of random vibration per paragraph 3.2.5.3.1.1 and the survival of the unit under the endurance levels of random vibration per paragraph 3.2.5.3.1.2. The random vibration tests were that of MIL-STD-810, Method 514.2, Procedure IA. All requirements were met. Details of the test are as follows:

Test Item: TRFS S/N 102

Spec: QTP 8.3
MIL-STD-810C, Method 514.2, Procedure IA
(general requirements)

Test Completion Date: 12/10/86

Test Facility: EG&G, Salem, MA

Procedure/Results - Performance Level Vibration:

1. The test unit was attached to an adapter plate, mounted on the vibration table and electrically set up per Figure 7.4.3.1.

2. The unit, energized, was exposed to the random vibration levels of QTP Table 8-1 (Z axis) and 8-2 (X and Y axes) for 30 minutes per axis. During exposure, the phase noise, output frequency and voltage were measured. There was no observable change in the output voltage. The phase noise was within specifications as shown in Figure 7.4.3.2 and the following table:

| Offset from Carrier | Specification | X Axis | Y Axis | Z Axis |
|---|---|---|---|---|
| 1 Hz. | > 60 dB | 77. | 75. | 67. |
| 100 Hz. | > 80 dB | 120. | 95. | 111. |
| 1 k Hz. | > 95 dB | 133. | 132. | 124. |

The output frequency error, determined from the slope of the phase difference between the TRFS being vibrated and the reference, was within specification:

| Specification | X Axis | Y Axis | Z Axis |
|---|---|---|---|
| $5 \times 10^{-10}$ | $<1 \times 10^{-11}$ | $2 \times 10^{-11}$ | $6 \times 10^{-11}$ |

3. After exposure, the unit was inspected and no damage observed. A Functional Test was performed and passed.

Procedure/Results - Endurance Level Vibration:

1. The test unit was attached to an adapter plate and mounted on the vibration table.

2. The unit, deenergized, was exposed to the random vibration levels of QTP Table 8-3 (Z axis) and 8-4 (X and Y axes) for two hours per axis.

3. After exposure in each axis, the unit was inspected and no damage observed. A Functional Test was performed and passed.

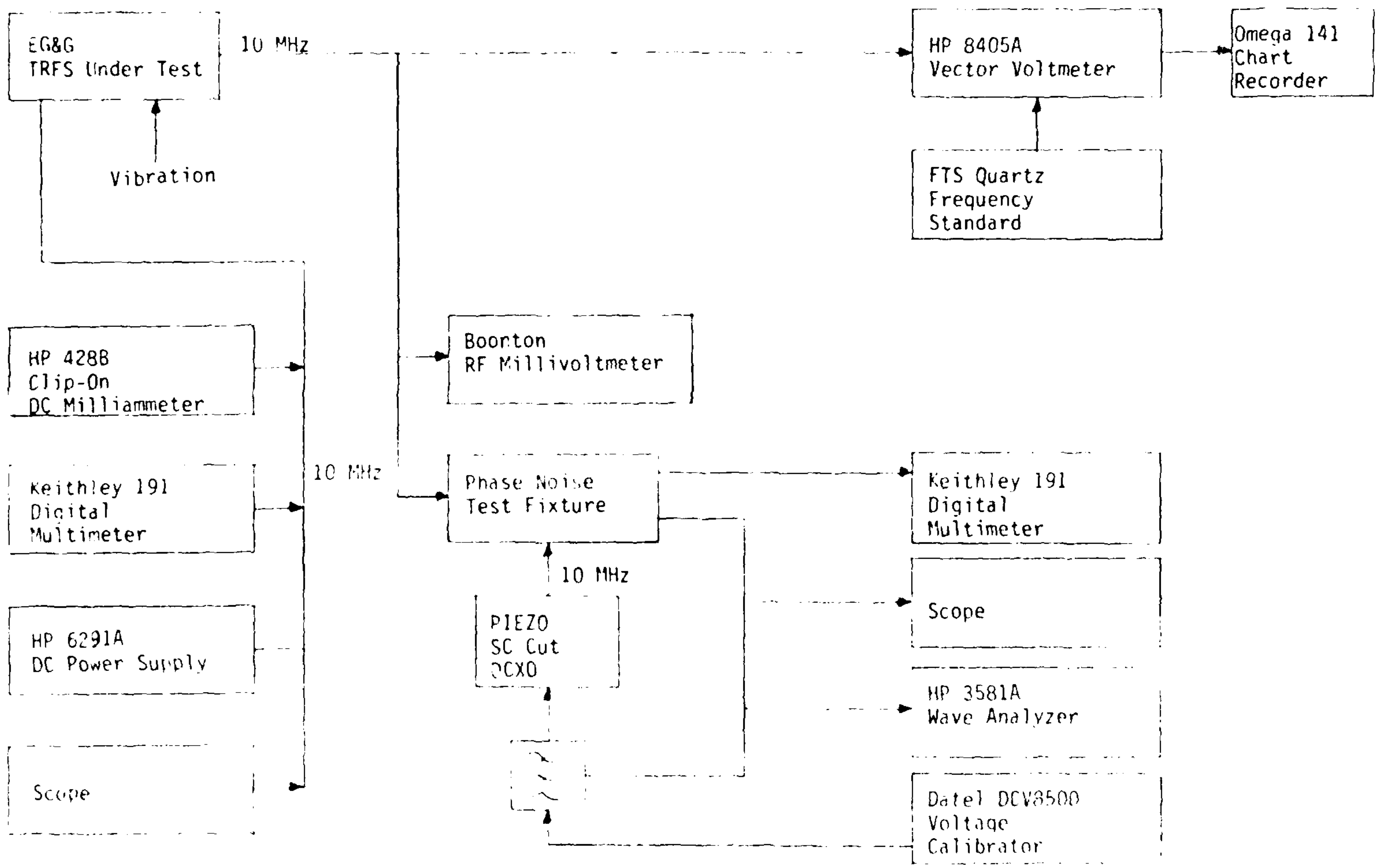



Figure 7.4.3.1
Random Vibration Test Setup

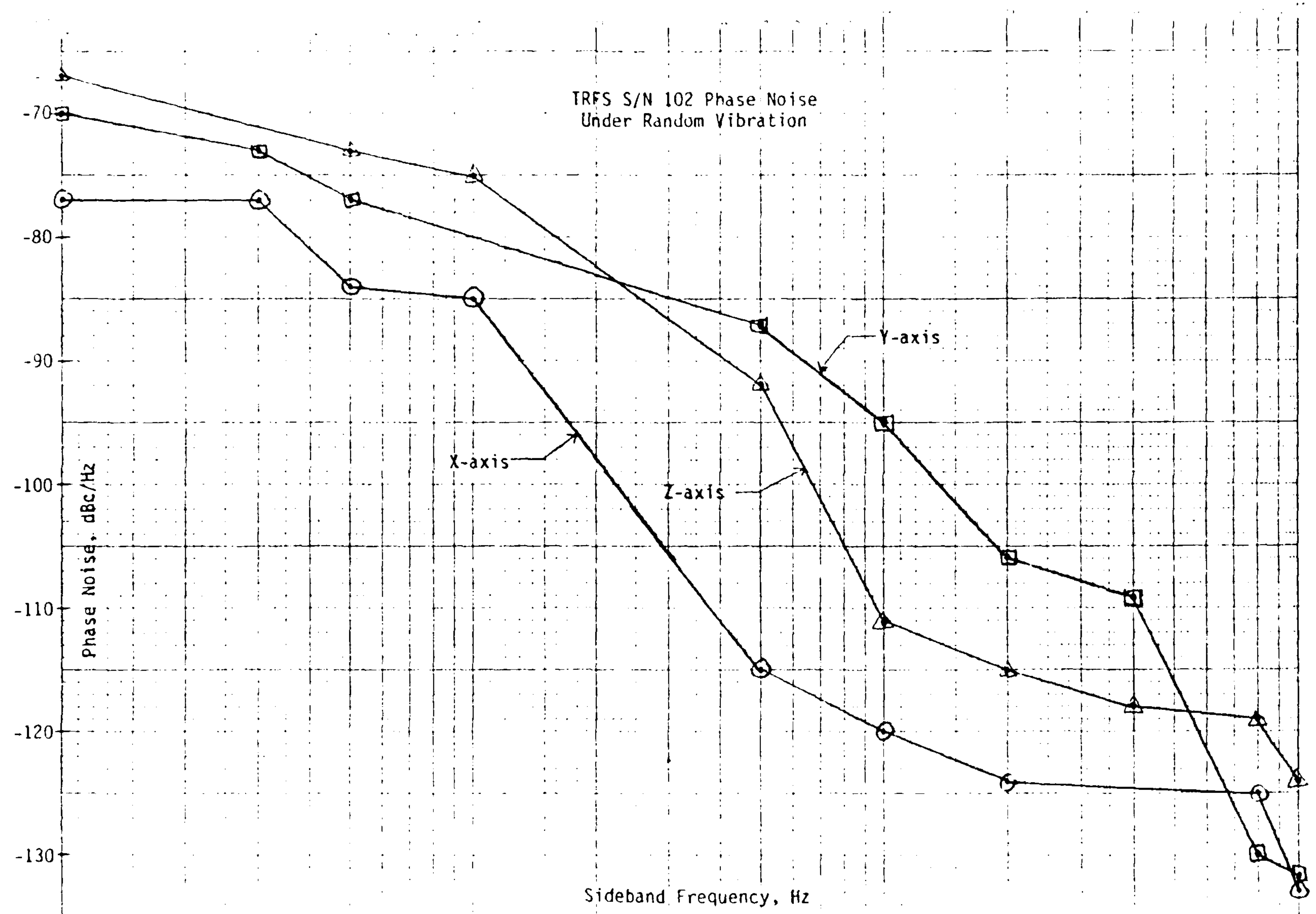

TRFS S/N 102 Phase Noise
Under Random Vibration
-70
-80
-90
-100
-110
-120
-130
Phase Noise, dBc/Hz
Y-axis
X-axis
Z-axis
1
10
100
1,000
Sideband Frequency, Hz

Figure 7.4.3.2

### 7.4.4 Sinusoidal Vibration

Sinusoidal vibration tests were performed on TRFS S/N 102 in accordance with paragraph 8.4 of the Qualification Test Plan. These tests involved the nonharmonic distortion (spurious) and frequency stability of the unit per paragraphs 3.2.1.8 and 3.2.5.3.2 respectively of the TRFS specifications under the minimum and maximum sinusoidal vibration levels of paragraphs 3.2.5.3.2 a. and 3.2.5.3.2 b. respectively. The sinusoidal vibration tests were those of MIL-STD-810, Method 514.2, Procedure VIII, Curve W and Procedure I. All requirements were met. Details of the test are as follows:

Test Item: TRFS S/N 102

Spec: QTP 8.4
MIL-STD-810C, Method 514.2, Procedure VIII, Curve W
and Procedure I (general requirements)

Test Completion Date: 12/9/86

Test Facility: EG&G, Salem, MA

Procedure/Results:

1. The test unit was attached to an adapter plate, mounted on the vibration table and electrically set up per Figure 7.4.4.1.

2. The test unit was exposed to sinusoidal vibration while energized. Output frequency and voltage and nonharmonic distortion at the vibration frequency were measured throughout vibration cycles. The frequency error was within the specification of $1 \times 10^{-9}$ measured with a gate time of 1 second below 20. Hz and 0.1 second above 20. Hz. Vibration levels were as follows:

   A. The unit, operating, was tested in accordance with MIL-STD-810C, Method 514.2, Procedure VIII, Curve W to the levels of QTP Table 8-5. Frequency cycling was from 5 to 500 to 5 Hz in 15 minutes for 3 hours per axis. The results are shown in Figure 7.4.4.2.

B. The unit, operating, was tested in accordance with MIL-STD-810C, Method 514.2, Procedure I. Frequency cycling was performed from 5 to 2000 to 5 Hz in 20 minutes for 60 minutes per axis to the levels of QTP Table 8-7 (Z axis) and 8-8 (X and Y axes). Vibration dwells were performed for 10 minutes at each of the frequencies of QTP Table 8-6. The results are shown in Figure 7.4.4.3.

Sinusoidal Vibration Test Setup

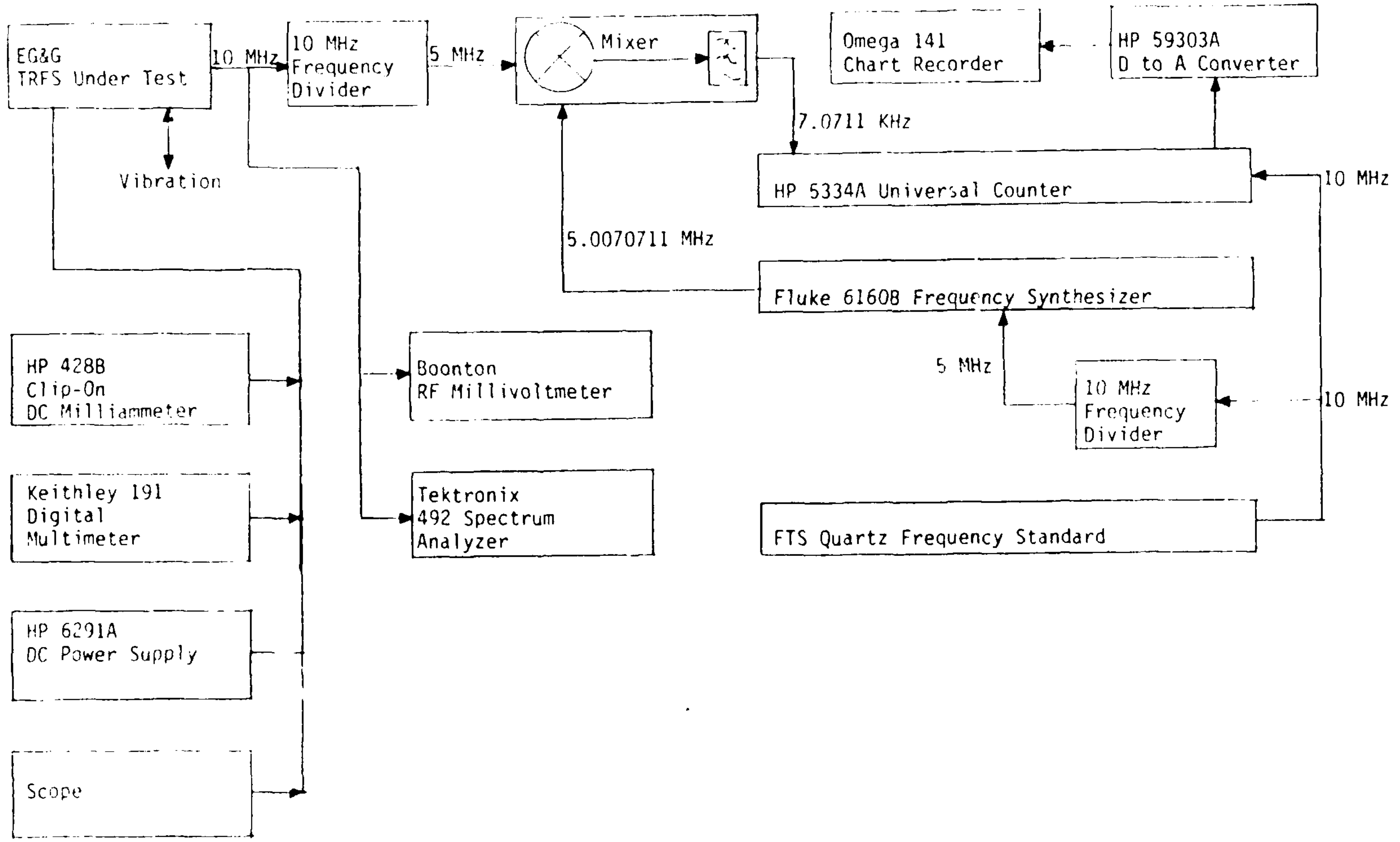
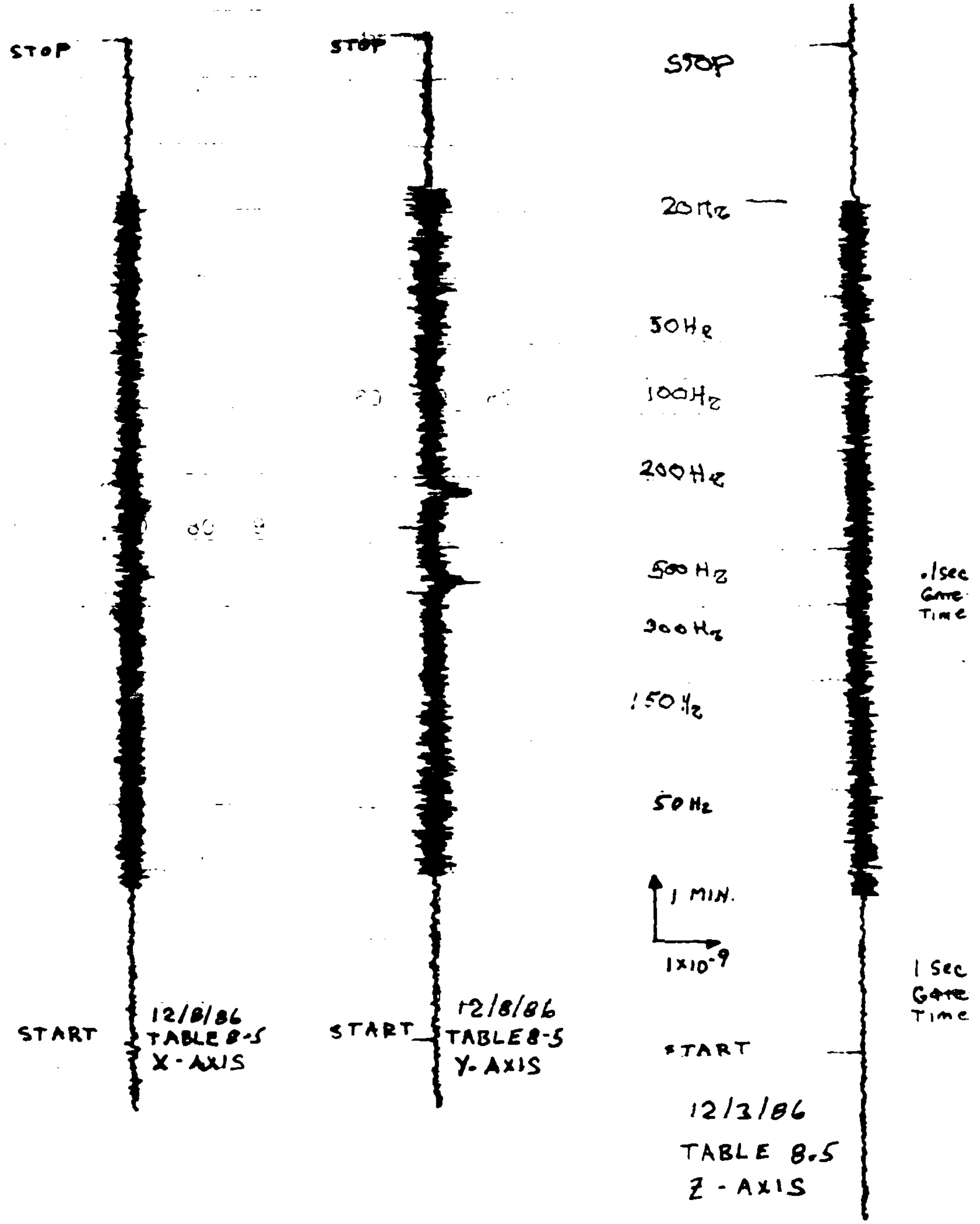
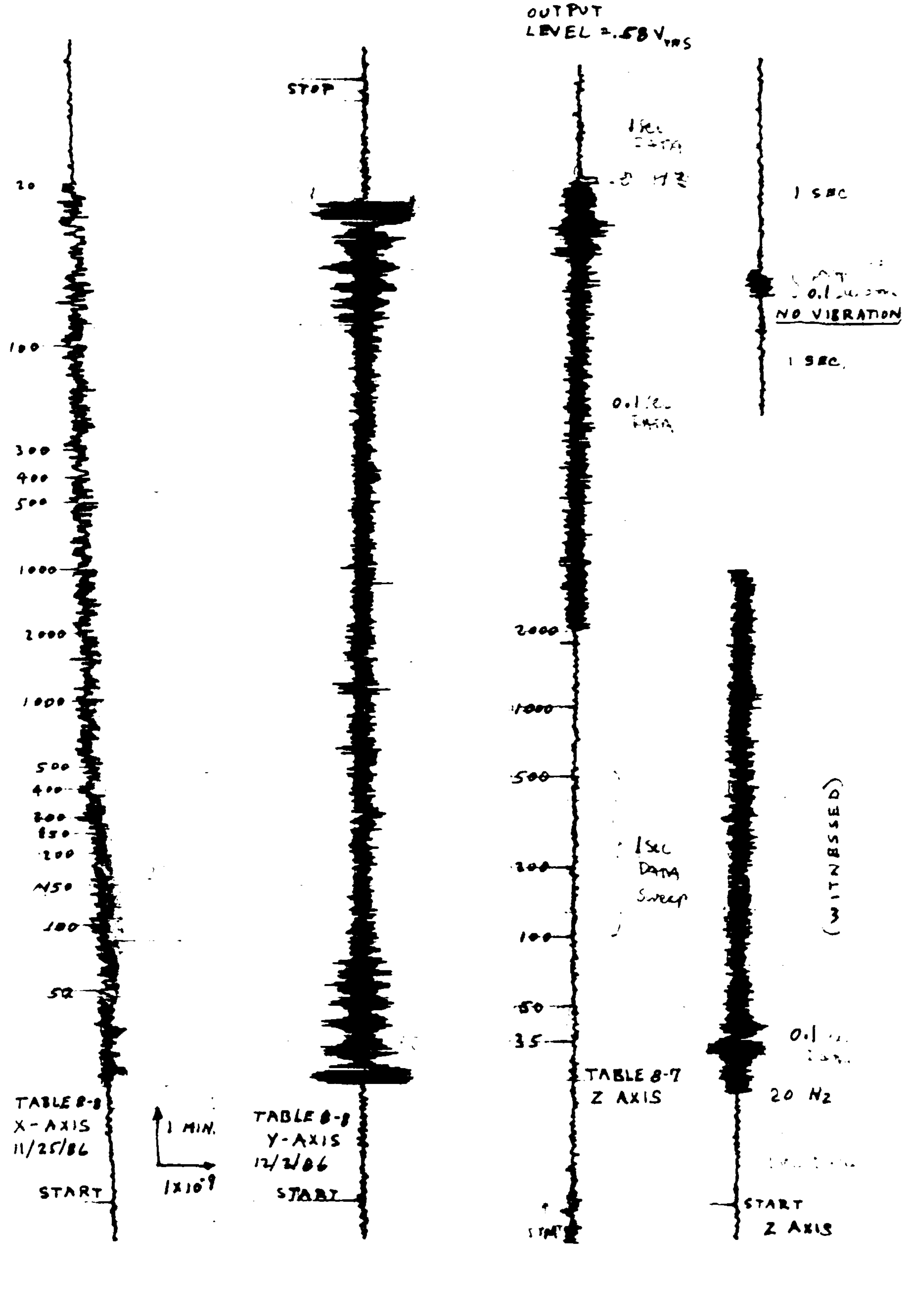



Figure 7.4.4.1




Frequency Error During Sine Vibration Table 8-5

Figure 7.4.4.2




Frequency Error During Sine Vibration Tables 8-7 & 8-8

Figure 7.4.4.3

7.4.5 Rain

A rain test was performed on TRFS S/N 102 in accordance with paragraph 8.12 of the Qualification Test Plan. This test involves the proper operation of the unit under the rain conditions of paragraph 3.2.5.10 of the TRFS specifications. The rain test was that of MIL-STD-810, Method 506.1, Procedure I. All requirements were met. Details of the test are as follows:

Test Item: TRFS S/N 102

Spec: QTP 8.12
MIL-STD-810C, Method 506.1, Procedure I

Test Date: 12/12/86

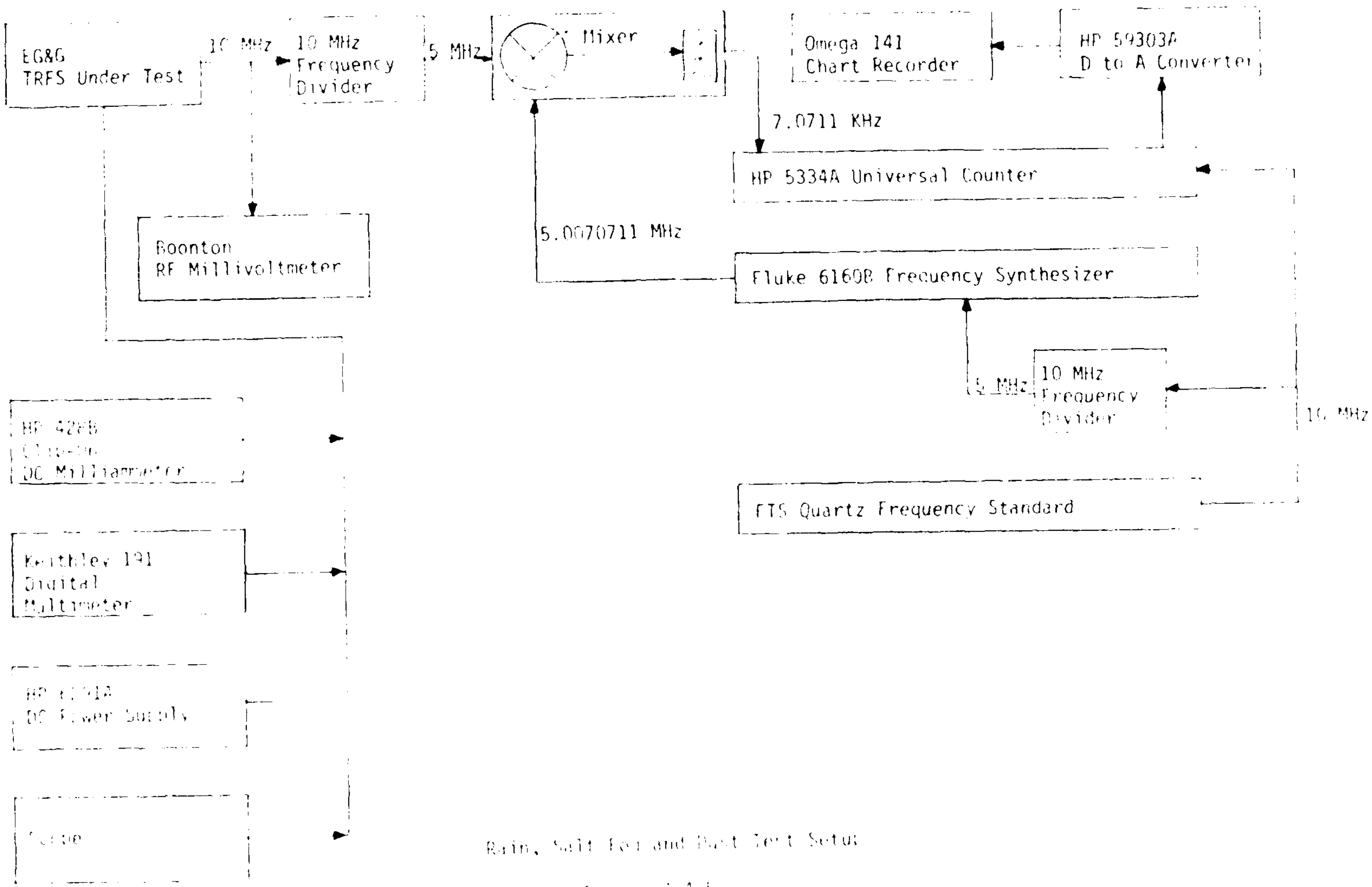
Test Facility: NTS, Acton, MA
(Purchase Order 23194)

Procedure/Results:

1. The test item was attached to a mounting plate and secured in the test chamber. Electrical connections were made per Figure 7.4.5.

2. Each of five sides of the test item, including the top but not the baseplate, was exposed to the specified wind and rain for 30 minutes (total exposure 2½ hours). During the last 10 minutes, power was applied to the test item, and the output frequency and voltage level were measured. Voltage level was normal, and at the end of the 10 minute operations, all values of frequency were within $5 \times 10^{-11}$.

3. The unit was examined for damage and none was observed.




Rain, Salt Fog and Dust Test Setup

Figure 2.4.5

### 7.4.6 Bench Handling

A bench handling shock test was performed on TRFS S/N 102 in accordance with paragraph 8.5 of the Qualification Test Plan. This test involved the survival of the unit after being subjected to the bench handling shock conditions of paragraph 3.2.5.2.1 of the TRFS specifications. The bench handling test was that of MIL-STD-810, Method 516.2, Procedure V. All requirements were met. Details of the test are as follows:

Test Item: TRFS S/N 102

Spec: QTP 8.5
MIL-STD-810C, Method 516.2, Procedure V.

Test Date: 11/24/86

Test Facility: EG&G, Salem, MA

Procedure/Results:

1. The outer cover was removed from the test unit.

2. The unit, nonoperating, was placed on a wooden bench top. Using each edge as a pivot, the opposite edge was raised to 4", 45$^{o}$ or the point of balance, (whichever came first) and allowed to drop freely. The unit was dropped four times on each of six faces.

3. The unit was examined for damage and none was observed.

4. A Functional Test was performed and passed.

7.4.7 Operational Shock

An operational shock test was performed on TRFS S/N 102 in accordance with paragraph 8.6 of the Qualification Test Plan. This test involved the survival and timekeeping performance of the unit under the operational shock conditions of paragraph 3.2.5.2.2 of the TRFS specifications. The operational shock test was that of MIL-STD-810, Method 516.2, Procedure I. All requirements were met. Details of the test are as follows:

Test Item: TRFS S/N 102

Spec: QTP 8.6
MIL-STD-810C, Method 516.2, Procedure I
(20 g, 11 ms half sine)

Test Date: 12/2/86

Test Facility: Associated Testing Labs, Burlington, MA
(Purchase Order 22971, item 2)

Procedure/Results:

1. The test unit was mounted on an adapter plate and attached to the shock machine (AVCO model SM-110). The electrical setup was per Figure 7.4.7.

2. Three shocks (20 g, 11 ms half sine) were applied in each direction of the X, Y and Z axes (18 shocks total). During exposure the unit was operating and the time keeping performance measured by the Spectracom 8150 Precision Phase Comparator. Using the 1 microsecond full scale setting, there was no observable timing error due to the shock pulses.

3. The unit was removed from the shock machine and examined. No damage was observed. A Functional Test was performed and passed.

Operational Shock Test Setup

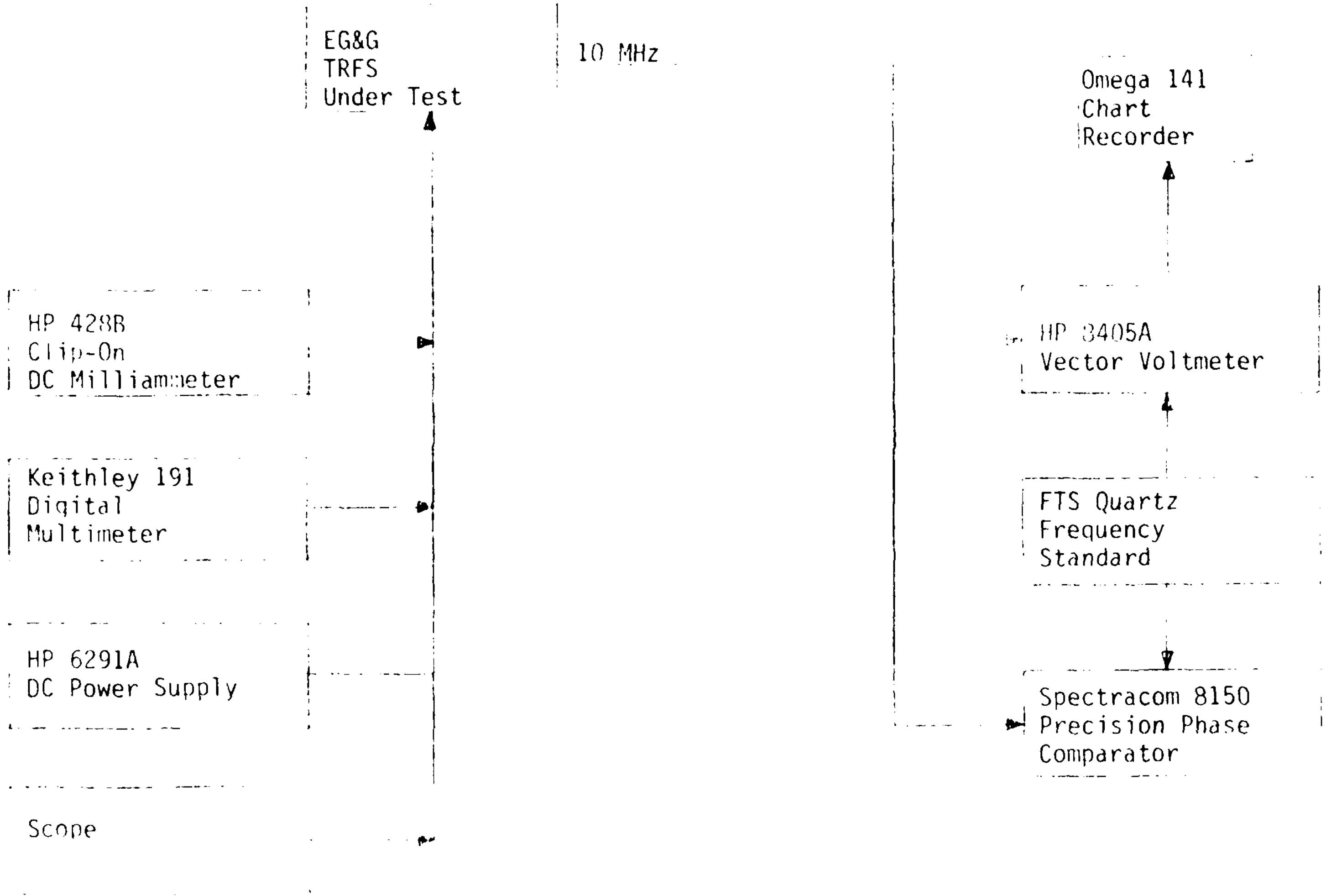



Figure 7.4.7

### 7.4.8 Acceleration

An acceleration test was performed on TRFS S/N 102 in accordance with paragraph 3.7 of the Qualification Test Plan. This test involved the output voltage and frequency stability of the unit per paragraphs 3.2.1.1 a. and 3.2.5.2.3 respectively of the TRFS specifications under the acceleration conditions of paragraph 3.2.5.2.3. The acceleration test was that of MIL-STD-810C, Method 513.2, Procedure II. All requirements were met. Details of the test are as follows:

| | |
|---|---|
| Test Item: | TRFS S/N 102 |
| Spec: | QTP 8.7<br>MIL-STD-810C, Method 513.2, Procedure II<br>(10.g) |
| Test Date: | 12/1/86 |
| Test Facility: | Associated Testing Labs, Burlington, MA<br>(Purchase Order 22971, item 1) |

Procedure/Results:

1. The test unit was mounted on an adapter plate and attached to the centrifuge (Genisco model 1230-1) at a radius of 42. inches. The electrical setup was per Figure 7.4.8. Redundant slip rings were used to bring out the power and output leads to reduce the effects of slip ring noise.

2. The unit was subjected to 10 g for at least 1 minute in each direction of the X, Y and Z axes (6 runs total). During acceleration, the output frequency and voltage were monitored. There was no observable change in output voltage. The highest observed frequency change was $3 \times 10^{-11}$ in the +Y axis, which was within specification ($4 \times 10^{-11}$).

3. The unit was removed from the centrifuge setup and inspected. No damage was observed. A Functional Test was performed and passed.

Acceleration Test Setup

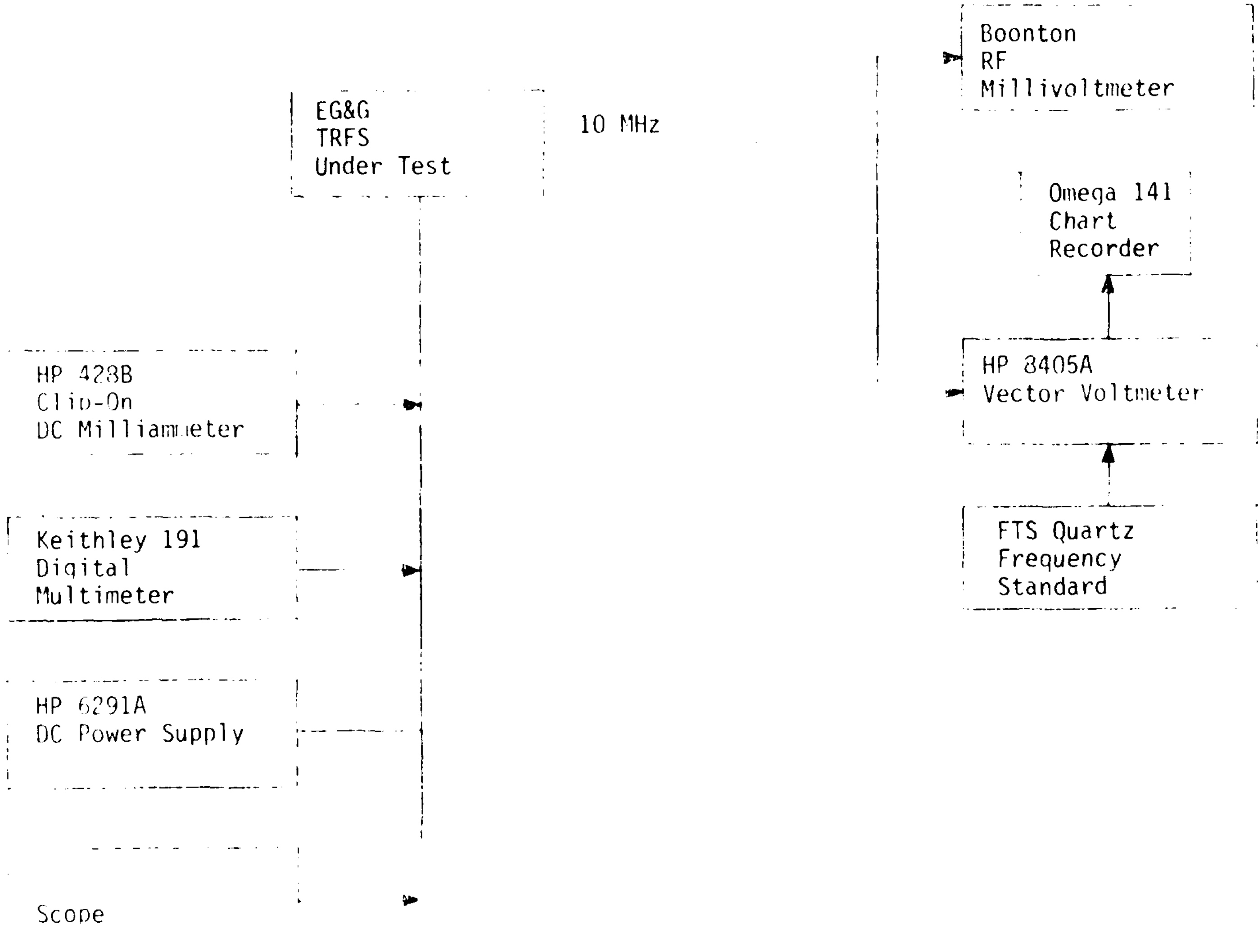



Figure 7.4.8

### 7.4.9 Acoustic Noise

An acoustic noise test was performed on TRFS S/N 102 in accordance with paragraph 8.8 of the Qualification Test Plan. This test involved the phase noise, output voltage and frequency stability of the unit per paragraphs 3.2.1.7 and 3.2.1.1 a. of the TRFS specifications and paragraph 8.6 f. of the test plan respectively under the acoustic noise conditions of specification paragraph 3.2.5.4. The acoustic noise test was that of MIL-STD-810, Method 515.2, Procedure I, Category A. All requirements were met. Details of the test are as follows:

Test Item: TRFS S/N 102

Spec: QTP 8.8
MIL-STD-810C, Method 515.2, category A, Procedure I
(140 dB, 30 minutes).

Test Date: 12/11/86

Test Facility: Noise Unlimited, Inc. Somerville, NJ
(Purchase Order 23179)

Procedure/Results:

1. The test chamber was set up to produce the specified acoustical noise spectrum.

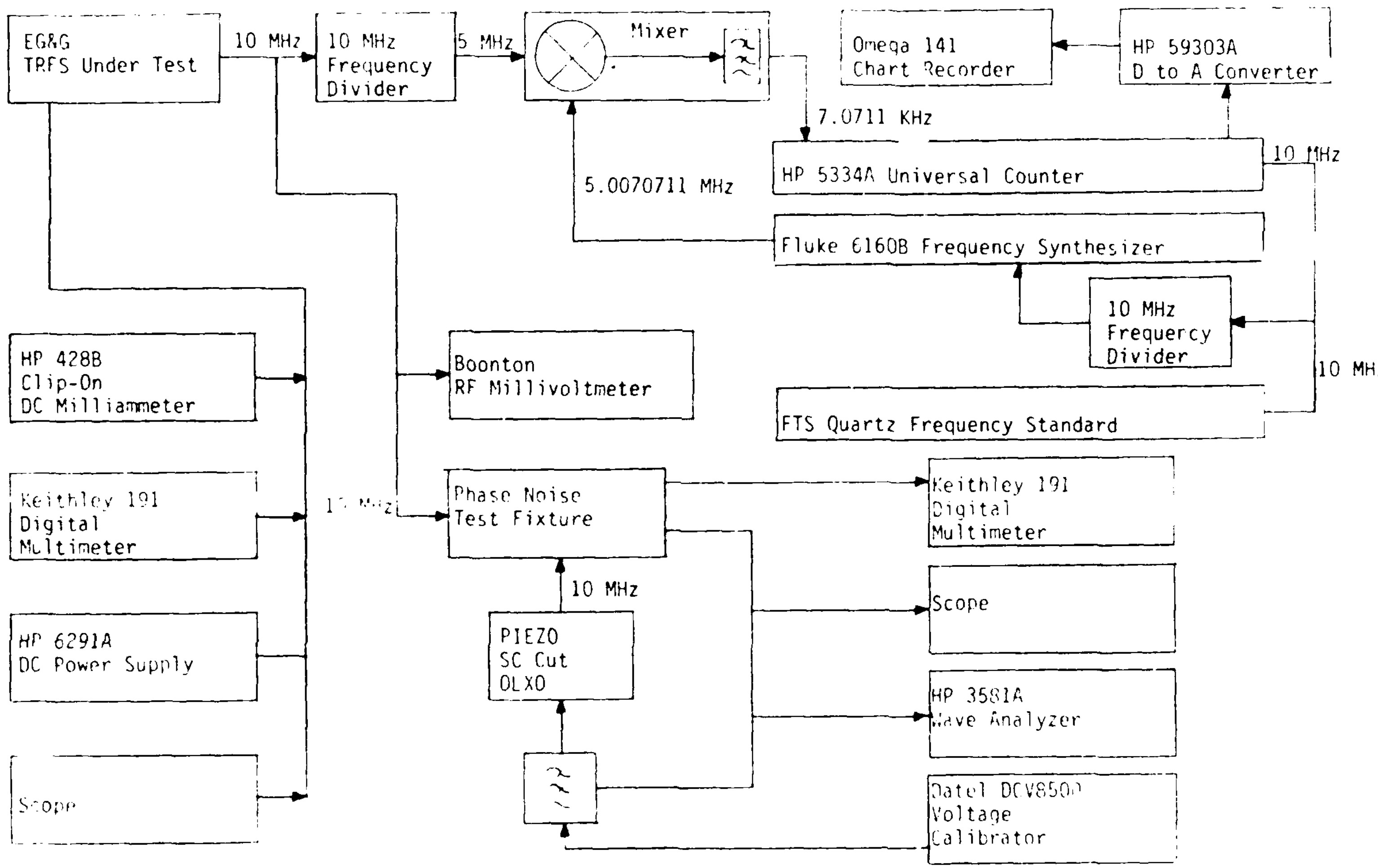
2. The test item was suspended by elastic cords and electrically set up per Figure 7.4.9.

3. With the unit operating, the acoustical noise was applied (140 dB for 30 minutes), and the output frequency and voltage and phase noise were measured. There was no observable change in output voltage. The highest frequency change was $1 \times 10^{-10}$ which was within specification ($5 \times 10^{-10}$). The phase noise was within specification:

| Offset from Carrier | Specification | Observed |
|---|---|---|
| 1. Hz | > 60 dB | 76 dB |
| 100. Hz | > 80 dB | 127 dB |
| 1. k Hz | > 95 dB | 138 dB |

4. After exposure, the item was examined for damage, and none was observed.

5. A Functional Test was performed and passed.




Acoustical Noise Test Setup
Figure 7.4.9

7.4.10 Humidity

A humidity test was performed on TRFS S/N 101 in accordance with paragraph 8.9 of the Qualification Test Plan. This test involved the proper operation of the unit under the humidity conditions of paragraph 3.2.5.5 of the TRFS specifications. The humidity test was that of MIL-STD-810, Method 507.1, Procedure II. All requirements were met. Details of the test are as follows:

Test Item: TRFS S/N 101

Spec: QTP 8.9
MIL-STD-810C, Method 507.1, Procedure II

Test Date: Starting 10/25/86 - 11/4/86

Test Facility: Associated Testing Labs, Burlington, MA
(Purchase Order 22111)

Procedure/Results:

1. Following preconditioning, a Functional Test was performed and passed.

2. The unit was subjected to five 48-hour cycles of temp-humidity as specified. Near the end of each 48-hour cycle, without opening the chamber, a Functional Test was performed and passed.

3. The unit was then conditioned for 24 hours, and a Functional Test performed and passed. The unit was inspected and no damage or corrosion observed.

7.4.11 Fungus

The TRFS design uses only components and materials that are inherently fungus inert, thereby meeting the fungus requirements of paragraph 3.2.5.7 of the TRFS specifications by analysis per paragraph 8.10 of the Qualification Test Plan.

7.4.12 Explosive Atmosphere

An explosive atmosphere test was performed on TRFS S/N 101 in accordance with paragraph 8.11 of the Qualification Test Plan. This test verified that the unit will not cause an explosion when operated in an explosive atmosphere per paragraph 3.2.5.8 of the TRFS specifications. The explosive atmosphere tests was that of MIL-STD-810, Method 511.1, Procedure I. All requirements were met. Details of the test are as follows:

Test Item: TRFS S/N 101

Spec: QTP 8.11
MIL-STD-810C, Method 511.1, Procedure I

Test Date: 11/7/86

Test Facility: Associated Testing Labs, Burlington, MA
(Purchase Order 22374, Item 1.)

Procedure/Results:

1. The test unit's outer cover screws were removed and the cover loosened to facilitate penetration by the explosive mixture. The unit was mounted on a heat sink and a thermocouple attached to the heat sink. The unit was placed in the test chamber and electrically connected.

2. The ambient temperature within the chamber was raised to 71°C. Approximately four hours were required for the chamber and test unit to reach temperature.

3. The specified procedures for chamber altitude, fuel addition and verification of mixture explosiveness were followed for the following altitudes: 50,000 ft., 40,000 ft., 30,000 ft., 25,000 ft., 20,000 ft., 15,000 ft., 10,000 ft., 5,000 ft. and sea level. The unit was operated during exposure and turned off and on at each test altitude. No explosion occurred.

4. After exposure, the unit was examined and no damage observed.

5. A Functional Test was performed and passed.

7.4.13 Salt Fog

A salt fog test was performed on TRFS S/N 101 in accordance with paragraph 8.13 of the Qualification Test Plan. This test verified that the unit functions and is not damaged when exposure to a salt atmosphere per paragraph 3.2.5.6 of the TRFS specifications. The salt fog test was that of MIL-STD-810, Method 509.1, Procedure I. All requirements were met. Details of the test are as follows:

Test Item: TRFS S/N 101

Spec: QTP 8.13
MIL-STD-810C, Method 509.1, Procedure I

Test Date: 11/8/86 - 11/12/86

Test Facility: Associated Testing Labs, Burlington, MA
(Purchase Order 22374, Item 2)

Procedure Results:

1. The test unit with connectors covered was attached to an aluminum plate and positioned, baseplate down, in the test chamber.

2. The unit, nonoperating, was exposed to the specified salt fog, for 48 hours.

3. At the end of the exposure, the unit was connected electrically and a Functional Test performed and passed. The unit was inspected for corrosion and none observed. (The unit was not washed).

4. The unit was then stored for 48 hours in an ambient atmosphere.

5. A Functional Test was performed and passed. The unit was inspected externally and with the outer cover removed, and no corrosion observed.

### 7.4.14 Sand and Dust

A sand and dust test was performed on TRFS S/N 101 in accordance with paragraph 8.14 of the Qualification Test Plan. This test verified that the unit functions and is not damaged when exposed to sand and dust per paragraph 3.2.5.9 of the TRFS specifications. The sand and dust test was that of MIL-STD-810C, Method 510.1, Procedure I. All requirements were met. Details of the test are as follows:

Test Item: TRFS S/N 101

Spec: QTP 8.14
MIL-STD-810C, Method 510.1, Procedure I

Test Date: 12/6/86 - 12/7/86

Test Facility: NTS, Acton, MA
(Purchase Order 23167)

Procedure/Results:

1. Mating connectors were attached to the test unit and the unit positioned in the test chamber with the front face toward the dust stream.

2. The test unit, nonoperating, was exposed to dust as specified (total 28 hours).

3. After exposure, accumulated dust was removed from the unit. A Functional Test was performed and passed. The unit was inspected, no damage was observed and there was no dust penetration into the contacts of the connectors or onto the unit electronics.

7.5 EMI Tests. EMI tests were conducted on EG&G TRFS S/N 101 in accordance with MIL-STD-461B for Class A1 equipment. These tests were performed by Sanders Associates and are described in their Test Report 4484 included as Appendix D to this Final Technical Report. The specific tests done were methods CE01, CE03, CE07, CS01, CS02, CS06, RE02, RS01, RS02 and RS03.

All tests were passed except for a minor outage in the CS02 test and a very minor outage in the CE03 test, both of which should be easily correctable in future hardware by a change in the electronic power input filter inductor. The CS02 problem was a very narrowband susceptibility of the 7th harmonic of the synthesizer frequency (~ 490 kHz) due to magnetic coupling between the filter inductor and an inductor on the adjacent rf board. This susceptibility was at a level about 6dB below the required threshold and was aggravated by inductor self-resonance.

The CE03 outage was only 1 dB at the ~ 50 kHz power switching rate. Both of these problems can be corrected by the substitution of a slightly higher value shielded inductor.

## 7.6 Aging Tests

Aging tests were conducted on both TRFS full scale engineering models after all other qualification testing in accordance with paragraph 10.1 of the Qualification Test Plan which calls for an aging test of from 7 to 30 days duration sufficient to establish the aging trend of the unit. Paragraph 3.2.1.4.1 of the TRFS specifications calls for a long-term drift less than $5 \times 10^{-10}$/year, an average of about $1 \times 10^{-11}$/week. The standard EG&G factory aging test calls for 7 days of aging data having a slope less than $1.5 \times 10^{-11}$/week to comply with a tighter drift spec., $6 \times 10^{-11}$ for the 1st month and $3 \times 10^{-10}$ for the next 11 months, since the drift can be expected to improve with time. A typical unit has a stabilized drift under $1 \times 10^{-11}$/month.

Both TRFS full scale engineering models were aged for a minimum of 7 days and both units had a drift under a $1.5 \times 10^{-11}$/week as shown in Figures 7.6.1 and 7.6.2.

# TRFS Aging Record

S/N 101

Scanner Ch. #25

Power Slot #16

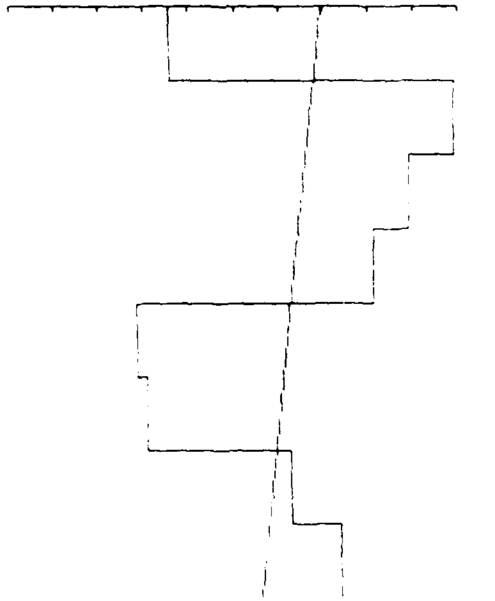
Vsupply = 26.4 Vdc

Year: 1986 Monitor Data:

| Date | LGT | CTL | CAV | LMP | CUR | Remarks |
|---|---|---|---|---|---|---|
| 12/15 | | | | | | Install |
| 12/16 | 28 | 54 | 67 | 64 | 19 | |
| 12/17 | " | 55 | 68 | 65 | 18 | |
| 12/18 | " | " | 67 | 64 | 19 | |
| 12/19 | " | " | 68 | 65 | 18 | |
| 12/20 | " | " | " | " | " | |
| 12/21 | " | " | 67 | 64 | 19 | |
| 12/22 | " | " | " | " | 18 | |
| 12/23 | " | " | 68 | " | " | Remove |

Plot:

```
Channel # 25  Frequenc  Data
Model #   TRFS     S/N    101
Time Scale   Day # 349 to 356
# Days       8
Freq Scale   +3.000E-011
         to  +5.000E-011
Min Freq     +3.569E-011
Max Freq     +4.982E-011
Avg Freq     +4.249E-011
Last Freq    +4.465E-011
Drift/Day    -3.502E-013
```




```
Channel # 25  Frequenc  Data
Model #     = TRFS
S/N         = 101
DAY          AVG FREQ
349          +3.709E-011
350          +4.982E-011
351          +4.785E-011
352          +4.623E-011
353          +3.569E-011
354          +3.610E-011
355          +4.251E-011
356          +4.465E-011
```

Fig. 7.6.1 TRFS S/N 101 Aging Data

# TRFS Aging Record

S/N 102

Scanner Ch. #30

Power Slot #20

$V_{supply}$ = 26.4 Vdc

Year: 1986 Monitor Data:

| Date | LGT | CTL | CAV | LMP | CUR | Remarks |
|---|---|---|---|---|---|---|
| 12/19 | 26 | 48 | 66 | 65 | 20 | Install |
| 12/20 | " | " | 67 | 66 | " | |
| 12/21 | " | " | 66 | 65 | " | |
| 12/22 | " | " | " | " | " | |
| 12/23 | " | " | " | " | " | |
| 12/24 | " | " | " | " | " | |
| 12/26 | " | " | " | " | " | |
| 12/27 | " | " | " | " | " | Remove |

Channel # 30 Frequenc Data
Model # = TRFS
S N = 102

| DAY | AVG FREQ |
|---|---|
| 353 | -1 356E-010 |
| 354 | -1 318E-010 |
| 355 | -1 661E-010 |
| 356 | -1 865E-010 |
| 357 | -1 599E-010 |
| 358 | -1 654E-010 |
| 359 | -1 558E-010 |
| 360 | -1 349E-010 |

Plot:

Channel # 30 Frequenc Data
Model # TRFS S N 102
Time Scale Day # 353 to 360
# Days 8

| | |
|---|---|
| Freq Scale | -2 000E-010 |
| to | -1 000E-010 |
| Min Freq | -1 865E-010 |
| Max Freq | -1 318E-010 |
| Avg Freq | -1 545E-010 |
| Last Freq | -1 349E-010 |
| Drift/Day | -1 029E-012 |

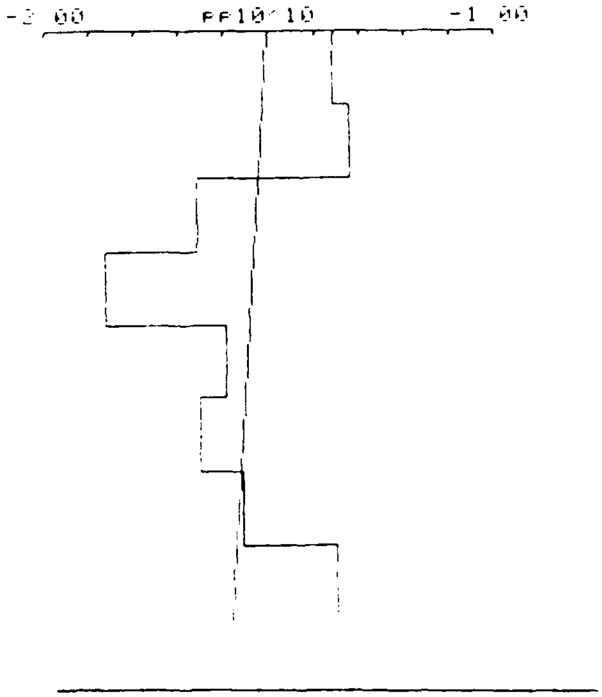



Fig. 7.6.2 TRFS S/N 102 Aging Data

## 8. CONCLUSIONS

All objectives of the Tactical Rubidium Frequency Standard development program have been met. The TRFS design work is complete and two full scale engineering models have been built, tested and delivered to the USAF. The TRFS design is now fully qualified to perform its intended function as a highly stable time and frequency source for demanding tactical military applications. The design discussed in this report advances the state-of-the-art in militarized rubidium standards in these important areas:

1. Very small size.
2. Extremely fast warm-up time.
3. Full performance at elevated ambient temperatures.
4. Performance under vibration.

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